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Vulnerability of Water Supply Systems to Drought

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VULNERABILITY OF WATER SUPPLY SYSTEMS TO DROUGHT

by

D. T. Jensen

A dissertation submitted in partial fulfillment
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of

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Approved:

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D. T. Jensen

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ABSTRACT

Vulnerability of Water Supply Systems to Drought

by

D. T. Jensen, Doctor of Philosophy

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The objective of this study is to develop a relatively simple and practical method for improving the availability and reliability of information about droughts to those responsible for water supply management and planning. The information technique developed provides an objective basis for the selection of water supply management alternatives during periods of drought. The derived drought information can assist water supply planners and managers in identifying priorities among proposed water supply developments from consideration of water supply vulnerability and existing drought severity levels.

Two drought indices are developed to achieve the overall objective of the study: (1) the drought severity index for describing the state of drought as it affects a water supply system and (2) the drought vulnerability index which indicates the probability of water shortage in a water supply system. In addition, the autoregressive, integrated moving average (ARIMA) method is used to develop a model representative of a water supply system and from the model synthetic data are generated using Monte Carlo methods. The synthetic data are utilized in the drought severity and vulnerability indices and the probabilities of future water shortage are calculated.

In this study the drought severity and vulnerability indices are conceptualized and tested for water supplies of three communities and three irrigation areas. Comparisons are made among the test cases. Excellent results are obtained from the municipality group and fair results are derived from the irrigation areas.

(179 pages)

CHAPTER I

INTRODUCTION

Background

In Utah and throughout the Western States, water shortages have occurred periodically. One of these occurred during the summer of 1977 as a result of the unusually low precipitation. The situation can become progressively worse in following years if there are several dry periods in succession. Under such circumstances, carry-over storage in reservoirs would be depleted, natural baseflows in streams would be reduced, and groundwater recharge would be decreased resulting in cessation of spring flow. Other springs would be diminished by increased drawdown in wells. Small rural communities which depend on springs or surface water supplies that are susceptible to drought would be impacted worst. The current concern of the possibility of a sequence of dry years may prove to be an over-reaction to a passing climatologic event. However, the present drought related problem does serve as a stimulus to assess the vulnerability of small rural water supply systems to drought. A sound basis for establishing the degree of adequacy or vulnerability to drought is needed.

In one sense, the cause of drought is precipitation amounts that are too low to sustain water use practices which are dependent upon average or normal precipitation. In another sense, drought may be caused by increased demands upon a water supply. The National

Weather Service (1977) reports that precipitation over most of Utah was between 25 percent and 50 percent of the 1968-1972 average for the months between October 1976 and February 1977. The true impact of the drought on water users will be related to the quantity of water furnished relative to demand. In other words, if precipitation is only 10 percent of average and most water demands are met then the "drought" has not resulted in losses to water users. On the other hand, if precipitation is 90 percent of average and water demands are not met, the period could be classified as a drought. Thus the fact that precipitation is below "an average" amount is not a meaningful indicator of the severity of a drought. If, for example, an irrigation company has large carry-over reservoir storage at the beginning of a drought, it may be able to furnish water in sufficient quantities to meet all demands placed on it in the short run. Therefore, the severity of drought is related to: (a) the degree to which the normal quantity of precipitation has come to be relied on for supplying water users, and (b) the facilities available for storing precipitation received in the past. The concept of the degree of use when there is no shortage of supply is utilized in developing a drought severity index in this study.

The vulnerability of a particular water supply system is dependent not only on the availability of water in the natural hydrologic system, in reservoir storage and in the groundwater system, but it also depends on the operating policies of the water supply manager and the capacity and type of supply facilities available. Naturally there is concern to minimize the expected loss from water shortage during the duration of the drought; but information is commonly inadequate for this purpose. If the probability of a shortage with a given drought severity could be quantified, then it would be possible for engineers and planners to assess the need for upgrading the supply facilities. The Utah Division of Water Resources manages an interest free revolving fund that is used to finance loans for upgrading water supply systems. A basis for the priority for receiving loans could be the relative drought vulnerability of the applicant supply systems. A drought vulnerability index could also be used by the State Engineer as a factor to be considered when allocating limited water supplies during a drought. An index capable of describing the vulnerability of a water supply system to drought is developed and tested in this study.

Purpose of Study

The overall objective of this research is to develop a relatively simple and practical method for improving the availability and reliability of information about droughts to those responsible for water supply management and planning. This information provides an objective basis for the selection of effective water conservation measures during periods of "drought." The methods will be useful for planners to identify priorities among proposed water supply developments from the consideration of water supply adequacy and vulnerability.

To achieve the overall objective of this research, two indices are developed: (1) a drought vulnerability index for indicating the probability of water shortage in a water supply system; and (2) a drought severity index for describing the state of a drought as it affects the availability of water for beneficial use. In addition, a tool for planning for future water supplies is developed using synthetic water supply data generated from a sophisticated time-series model.

The research described herein includes the conceptualization and preliminary testing of the vulnerability and drought severity indices. Testing is accomplished using data collected from rural domestic water supply and irrigation systems in Utah. Additional data from newspapers and climatic indices are also used as a supplement.

Significance of the Study

During drought periods a great deal of political pressure develops to restrict water use and to provide funds to augment existing water supplies. In dealing with the public and the press during emergency situations, differences in how water supplies are affected by drought are often overlooked. Also, water conservation practices vary widely among users. An index of drought that encompasses more of the factors directly related to water supply would be more useful for the management of water supply systems and for planning purposes than are the present indices based largely on weather and climatic information. In the absence of objective information for comparing alternatives, the selection of supply augmentation projects becomes dependent on political influence. The measures that are implemented are less effective because of the inavailability of sufficient information for planning purposes.

An important contribution to overcoming this difficulty is to make available to water supply managers and planners dependable information on drought conditions and drought effects on individual water supply systems. The probability of water shortage at the present time or in the immediate future (drought vulnerability) and the probable degree of shortage (drought severity) provides much of this needed information.

Research Design

To achieve the major objective of developing a practical method to improve the availability of information about droughts, drought severity and drought vulnerability indices are developed. These indices are tested using data collected from three municipalities and three irrigation areas, each having a different type of water supply system. The municipalities include:

1. Milford City, Utah, whose water is supplied by ground-water pumping.

2. Monticello City, Utah, whose water is supplied by spring and surface streamflow, with storage facilities.

3. Orangeville City, Utah, which depends upon surface streamflow entirely for culinary water supply.

The irrigation areas include:

1. The Logan irrigation area, located in Northern Utah, and

depends upon the Logan River for irrigation. No storage facilities are available.

2. The Milford irrigation area, located near Milford, Utah, depends only upon ground-water pumpage for irrigational purposes.

3. The Oberto Ditch irrigation area, located near Helper, Utah, obtains irrigation waters from the Price River as well as from storage facilities in the Schofield Reservoir.

In order to develop the drought indices for planning purposes, the Box-Jenkins univariate time-series methodology is used. A model is constructed from the Logan River data and 200 years of synthetic streamflow are generated. Canal diversions are derived from the synthetic streamflow using legal constraints. The drought severity and vulnerability indices are calculated for the 200 year period.

Statistical analysis of the drought severity index used includes the normal, Pearson Type III, Gumbel, Rayleigh, Gamma, Beta, Log-normal and Log-Pearson Type III distributions. The Chi-square test is used to determine which distribution has the "best" fit. This distribution is then used to determine the probability that the drought severity index will exceed a certain value. These probabilities are used to define the vulnerability of each water supply system to drought. The drought indices are verified using general drought periods as defined by the Palmer Drought Index and public opinion as found in historical newspaper articles.

Delimitations and Limitations

This study is limited to three small, rural municipalities and three irrigation areas which depend upon varied water supply systems. The data used to calculate the drought vulnerability and drought severity indices are average monthly data for the municipalities, seasonal data for two of the irrigation areas and monthly data during the irrigation season for the third irrigation area.

Presently, there is no "drought index" available with which to verify the drought vulnerability and drought severity index as developed in this study. Verification is commonly accomplished by comparing the results of accepted models with the proposed model results which were based on the same or similar data. Direct comparison of a meteorologically based model such as the Palmer Index is not sufficient because the same parameters are not measured. Questionnaires or personal interviews involving individuals of drought affected areas provide excellent information about present drought conditions, but drought information about the past 30 to 40 years is more difficult to obtain accurately, especially in defining "marginal" drought conditions. Newspaper articles on drought are an indication of public opinion and the importance of water. Because of the lack of a suitable verification technique, general severe "drought" years are defined by the regional Palmer Drought Index and by a perusal of daily newspaper microfilm records for the 1958-1976 period. The general periods of drought are compared with calculations of the drought severity index as developed in this study.

Summary of Contents

Chapter II contains a literature review. The review is divided into three parts: (1) a review of the explanation of drought, (2) a review of drought related concepts including general definitions, concepts and statements, and (3) a review of the usefulness of definition and methods.

The methods and procedures are established in Chapter III. The drought severity and drought vulnerability indices are established. Areas of study are defined and a detailed physical description of the six geographical locations studied. Water supply-demand functions are defined for each area. A time-series model for the generation of synthetic data is developed for planning purposes. Methods of statistical analyses of the data and evaluation procedures are set forth.

Chapter IV contains the results and discussion of the results as they apply to each pilot area. An application of the usefulness of the results is included. A summary of the entire study and recommendations for additional research are included in Chapter V. An appendix found at the end of this work includes tables of data, results and computer program information that is used in the study.

CHAPTER II

LITERATURE REVIEW

Introduction

The review of literature is divided into three parts: (1) a review of the explanation of drought, (2) a review of drought related concepts including general definitions, concepts and statements in tabular form for easy reference, and (3) a review of the usefulness of definitions and methods.

Review of Explanation of Drought

Causal factors

The occurrence of a drought depends upon the changes of hydro-meteorological characteristics within a region. These characteristics depend upon atmospheric motion which result from characteristics of large land masses, oceans, and insolation (Yevjevich, 1967).

Oceanic areas and the distribution of warm and cold circulation and region regulate the composite of overlying air masses. These air masses as they progress inland, both change and are changed by the character of the land over which they pass.

The atmospheric motion and variation is the main reason for the reduction in the frequency of large storms and the decrease in productivity of precipitation for a region. However, another region usually benefits from an increased number of storms and precipitation.

When the numbers of large storms is decreased and when the amount of precipitation produced from storms is lessened, the resulting runoff is also decreased. Over a duration of time, the decreased precipitation and runoff result in drought conditions for an area.

Problems of prediction

Because droughts are a function of atmospheric motion, oceanic changes, continents and land forms and other causal factors as well as definitional problems, droughts are difficult to predict (Yevjevich, 1967).

Current methods of weather prediction integrate dynamic equations of the atmosphere for results. Presently there exists a large number of synoptic data points to define initial conditions and boundary conditions. These criteria are merged to predict weather for 1 to 5 days with the most precision in the 12 to 36 hour range. The philosophy is to use more data point, more complex and faster computers and more sophisticated equations to obtain better and longer-term forecasts. Lack of funds, inflation, and more automation (less observers) seem to be limiting factors. Also turbulence and mesoscale vorticity patterns appear to be governed by the laws of probability and therefore are not easily subjected to deterministic prognostication. When weather patterns and atmospheric motion can be predicted for long terms with some reliability, then droughts will also be predicted with reliability.

There exist very few certainties in drought study. Uncertainty of hydrology in water system design arises because of the inability to forecast the future sequence of flows that a water supply system will encounter during its design life. This is of little concern to the water users as long as the natural supply is stable and comparatively large when compared to demands. Shortages or drought conditions under these conditions can then be ignored.

The basic philosophy used by water system planners has been that the recent past is the key to the near future. However, it is not agreed upon as to what is the "recent past" or "near future" (Stockton, 1977; Matalas and Fiering, 1977; Schwarz, 1977; and Dracup, 1977). The tremendous effort and expense recently dedicated to climatic change, cycles and periodicity has been lost in a contest of opinions with data justifying each theory (Alexander, 1974; Boncher, 1975; Fritts, 1965; Griffiths, 1974; Matthews, 1976; Schneider and Temkin, 1977; Shapley, 1953; United States Committee for the Global Atmospheric Research Program, National Research Council, 1975; Wolkomir, 1976). Unless there are significant breakthroughs, it is not likely that these studies will contribute very much to drought prediction.

A Review of Drought Related Concepts

Drought is a happening that people experience rather than data as instruments would record them. Because of this there is a wide diversity in the ways different fields of study view droughts.

The engineer may view drought as a set of variables affected by precipitation, runoff and water storage. The geophysicist may consider climatological, hydrometeorological, limnological, glaciological, or soil aspects. The agriculturist views drought as it affects various crops. The economist is concerned with how decreases in precipitation affect human activity and the satisfaction derived therefrom. Each water user has its own concept of drought and the concept changes with the user's conditions (Yevjevich, 1967).

Drought is normally perceived in terms of its problems and impacts. Generally, drought is spoken of as a function of one or a combination of many variables. These data may range between specific, point measurements, and averages of data for large areal extents. Some of the variables that have historically been used to measure drought include radiation, precipitation, evapotranspiration, effective precipitation, streamflow runoff, tree rings, varves, natural storage, artificial storage, economic, social and psychological indicators. In addition, it is necessary to determine the time extent of both data requirements as well as for the definitional requirements for drought.

All of these variables may be necessary for an objective definition of drought. Any one or a combination may be used by able scientists in many fields to describe the conditions which prevail in and around a drought stricken area. These are used to assist them in answering questions pertinent to their field of expertise, while definitions and concepts of extreme importance in other fields are ignored. Hence, a precise definition of drought in one field has little or no meaning in an unrelated field. Yet each scientific field is correct in its own definitions when evaluated by its own criteria. Indeed a meteorological drought may have little affect upon a water supply system with adequate storage facilities. Also as Tannehill (1947) so aptly noted, the rainfall in the worst drought ever experienced in Ohio would be abundant moisture in Utah. Table 1 includes a summary of some of the concepts of drought.

A Review of the Usefulness of Definition and Methods

A bibliography of drought was compiled by Palmer and Denny (1971) and includes abstracts of worldwide drought related problems. The bibliography is an excellent compilation and is organized for easy use.

The Palmer Drought Index (Palmer, 1965) is a function of meteorological parameters and soil moisture. It presents an objective numerical approach to drought and permits an objective evaluation of climatic events. Developed for the Midwest for agricultural needs, this index is presently calculated for the many climatic regions in all of the United States. The Palmer Drought Index has not received wide acceptance although the Environmental Data Service of the National Oceanic and Atmospheric Administration publishes weekly maps of the index of the United States during the growing season. Palmer, himself (Richardson, 1977) has had reservations about using the index in areas other than the mid-east but analysis of the Utah area, with the exception of the Dixie Climatic Region, shows that the index performs quite well. The Palmer Drought Index can be refined and fitted to each local area. It was determined to use the index as published (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service. 1931-1977) for this study.

The Gumbel (1963) method of analysis of drought problems uses the definition that a drought is the smallest annual values of mean

Table 1. Drought concepts.

GENERAL DEFINITIONS, CONCEPTS AND STATEMENTS

Reference	Concept
Tannehill (1947)	"But we have no good definition of drought. We may truthfully say that we scarcely know a drought when we see one. We welcome the first clear day after a rainy spell. Rainless days continue for a time and we are pleased to have a long spell of such fine weather. It keeps on and we are a little worried. A few days more and we are really in trouble. The first rainless day in a spell of fine weather contributes as much to the drought as the last, but no one knows precisely how serious it will be until the last dry day is gone and the rains have come again . . . We are not sure about it until the crops have withered and died . . ."
Linsley, Kohler, Paulhus (1949)	Drought is a sustained period of time without significant rainfall, ("sustained" and "significant" are not defined).
Oxford English Dictionary (1961)	1. The condition of being dry; dryness, aridity, lack of moisture (archaic) 2. Dryness of the weather or climate; lack of rain (current sense) 3. Dry or parched land, desert (obsolete, rate) 4. Thirst (archaic and dialect) 5. Attributive and combined
Hounam, et al. (1975)	Thornthwaite in 1947 noted that drought cannot be defined as a shortage of rainfall alone. Deacon, et al., in 1959 realizing the problem involved, urged that definitions of drought be systemized in relation to effectiveness of precipitation in different climates. V. P. Subrahmanyam in 1967 noted that to the meteorologist a drought is a rainless

Table 1. Continued.

GENERAL DEFINITIONS, CONCEPTS AND STATEMENTS	
Reference	Concept
	situation for an extended period. To the agriculturalist, drought is a shortage of moisture for crops. The economist view is that of a water shortage adversely affecting the established economy of the region. The hydrologist considers drought as diminution of streamflow or lower surface and underground water levels. Water shortage is basic to drought conditions and is a relative rather than an absolute condition.
World Book Encyclopedia (1975)	Drought occurs when the average rainfall for a fertile area drops far below the normal amount for a long period of time.
PRECIPITATION AND DROUGHT CONCEPTS	
Cole (1933)	Cole used 15 day periods without measurable rainfall during May-September and used 20 day periods without rainfall during the rest of the year. He noted also that these rules (as well as others) must be applied with judgment.
Hoyt (1936)	A drought exists when precipitation falls to 95 percent of the mean.
Tannehill (1947)	Drought is a spell of dry weather. Drought can be viewed as a valley of rain deficiency in the broad sweep of time and weather. At one time in European Russia, drought was defined as a period of ten days with rainfall not exceeding 0.20 inches. The U.S. Weather Bureau has defined drought as a period of thirty days or more with deficient rainfall and not exceeding 0.25 inches in any 24 hour period. In the early 1900's however, the definition was

Table 1. Continued.

PRECIPITATION AND DROUGHT CONCEPTS (cont.)	
Reference	Concept
	21 days or more with precipitation 30 percent or more below normal. In England an absolute drought was a period of 14 consecutive days without 0.01 inch on any one day and a partial drought was a period of more than 28 days with precipitation averaging not more than 0.01 inch per day. A precise definition could be ". . . a period of deficient rainfall which is seriously injurious to vegetation."
Brooks (1950)	In East Africa, severe drought is defined as a period when rainfall is "barely sufficient." In Britain, severe drought is classified as a period lasting more than six months with annual precipitation less than 68 percent. Droughts are generally more severe in southeast England where precipitation is lower and more variable from year to year. In the USA, drought is defined as a deficiency of rainfall coupled with increase in population and groundwater mining.
Selyaninov (1957)	Rotmistrov's 1913 classical definition is that a drought is caused by a lack of rain which gives rise to insufficient soil moisture and thereby retards plant development. Drought results in a measurable rise in air temperature and associated decrease in air humidity. Plant behavior is the final criterion of drought, the degree of drought is estimated from the deviations of harvest from average harvest values. In 1930 an index of humidity (drought) was proposed that used the ratio of the total rainfall to the sum of temperatures multiplied by a factor of 0.1. The

Table 1. Continued.

PRECIPITATION AND DROUGHT CONCEPTS (cont.)	
Reference	Concepts
	agrometeorological drought index is defined as less than 0.6 to 0.7. The corresponding harvest decrease was in the order of 20 to 25 percent.
Huschke (1959)	Drought is defined as an abnormal period of dry weather sufficiently long that it causes a serious hydrologic imbalance. Severity depends upon the degree of moisture deficiency, duration and size of area affected. In Britain, this period is at least fifteen continuous days with no measureable precipitation. Season makes no difference. A partial drought is a period of at least twenty-nine days during which the average rainfall does not exceed 0.01 inches. In Köppen's classifications the climates are defined strictly by the amount of annual precipitation as a function of seasonal distribution and annual temperature. In Thornthwaite's classification, drought occurs when a moisture index is less than zero and when seasonal water surplus does not counteract seasonal water deficiency. Dry climates are subdivided according to values of humidity index as: little or no water surplus; moderate winter water surplus; moderate summer water surplus; large winter water surplus; and large summer water surplus.
Hudson and Hazen (1964)	These authors recognize the standard U.S. Weather Bureau definition in the United States but note that in: Bali: a period of 6 days without rain is a drought Libya: 2 years without rain is a drought Egypt: any year the Nile River does not flood is a drought regardless of rainfall. Concept of drought refers to periods of unusually low water supply, regardless of demand for water in a specific place.

Table 1. Continued.

PRECIPITATION AND DROUGHT CONCEPTS (Cont.)

Reference	Concepts
Saarinen (1966)	Saarinen notes that it is easier to define a drought precisely after its occurrence than during the period in which it is becoming more and more severe. He also gives the following definitions: (1) A permanent drought is one where precipitation is never great enough to meet the needs of potential evapotranspiration. (2) A contingent drought is due to variations in precipitation from year to year. (3) A seasonal drought is one in which a season receives an inadequate amount of precipitation, though other seasons may receive adequate or even excessive precipitation. (4) An invisible drought is one which has borderline amounts of precipitation which is not quite enough to satisfy crop demands and shows up as decreased harvest yields. He quotes an early definition by Harry E. Weakly as "any period in which tree growth was reduced for five or more years has been considered to be a drought period."
Hounam, et al. (1975)	Tennessee Valley Authority defines drought as an interval of 21 days in which precipitation was no greater than one-third of normal. An Engineers' drought in Australia is three or more consecutive months with deficit of 50 percent from mean rainfall (Baldwin-Wiseman definition). The authors note Thornthwaite quoting Blumenstock that a drought was a period of 48 hours receiving less than 2.5 mm. They also note Conrad's definition of drought as a period during March through September of 20 (or 30) consecutive days or more without 6.4 mm of precipitation in 24 hours.

Table 1. Continued.

CLIMATIC AND EVAPOTRANSPIRATION CONCEPTS

Reference	Concepts
Baier and Robertson (1966)	A model is suggested for estimating the actual evapotranspiration (AE) from changes in soil moisture per zone as: $AE_i = \sum_{i=1}^{n} k_i \frac{S'_{j\,(i-1)}}{S_j} Z_j(PE_i)\ E\ -w(PE_i-\overline{PE})$ in which AE_i = actual evapotranspiration for day i ending at the morning deservation of day i + 1; $\sum_{j=1}^{n}$ = summation carried out from zone j=1 to zone j=n.; k_j = coefficient account for soil and plant characteristics in the jth zone.; $S'_{j(i-1)}$ = available soil moisture in the jth zone at the end of day i-1, that is, at the morning observation of day i.; S_j = capacity for available water in the jth zone; Z_j = adjustment factor for different types of soil dryness curves; PE_t = potential evapotranspiration for day i.; w = adjustment factor account for effects of varying PE rates on AE/PE ratio.; $\overline{PE}$ = average PE for month or season; k = coefficients to express the amounts of water in percent of PE. The coefficients k express the amount of water in percent of PE extracted by plant roots from different zones during the growing season.
Palmer (1968)	Severity of agricultural drought is defined in terms of the magnitude of the computed evapotranspiration deficit and expressed as a crop moisture index (CMI). Negative values of the CMI mean that evapotranspiration has been abnormally deficient.

Table 1. Continued.

CLIMATIC AND EVAPOTRANSPIRATION CONCEPTS (Cont.)

Reference	Concept
	The United States is mapped using this index on a weekly basis.
Sly (1970)	Sly suggests a climatic moisture index that expresses seasonal precipitation as a percentage of the water used by crop were stresses not allowed to develop. $$I = \frac{P}{P + SM + IR} \times 100$$ in which P = growing season precipitation SM = soil moisture available at beginning of the season IR = calculated growing season irrigation requirement
Sly and Baier (1971)	With the growing season defined as May through September, a climatic moisture index is used for country-wide (Canada) comparisons.
Hounam, et al. (1975)	The World Meteorological Organization lists Hounam, Trumble, and Prescott as using climatic boundaries for land use and for frequency of periods of non-effective rainfall (drought). Turc is noted for his formula for short drought periods (10-day period) $$E = \frac{P + a + V}{\left[1 + \left(\frac{P + a}{L} + \frac{V}{2L}\right)^2\right]^{1/2}}$$ in which E = evaporation a = estimated evaporation from bare soil V = a crop factor L = evaporation capacity of the air His annual formula is: $$E = \frac{P}{\left[0.9 + \left(\frac{P}{L}\right)^2\right]^{1/2}}$$

Table 1. Continued.

ECONOMIC AND SOCIAL CONCEPTS

Reference	Concept
Hoyt (1936)	When precipitation is not sufficient to meet the needs of established human activities, drought conditions may be said to prevail.
Saarinen (1966)	Saarinen notes that Kifer and Stewart define drought in terms of: 1. percent departure from normal rainfall 2. average crop and pasture conditions as a percent of normal. 3. percent increase or decrease in the number of cattle 4. amount of Federal Aid per capita The William G. Hoyt view is that a drought condition is created if, in the economic development of a region, man creates a demand for more water than is normally available. Humphreys notes that a drought occurs when shortage of rainfall causes distress to those who are dependent on rain.
Beran and Kitson (1977)	These authors note that rainfall, riverflow, storage, and distribution must be studied together and statements as to severity of drought should contain the parameters and durations used to calculate the severity.

METHODS OF ANALYSIS

Reference	Concept
Levitt (1958)	Drought is defined as a measure of the environment's drying potential. Atmospheric drought is proportional to the vapor pressure deficit of the air $D_a \propto p_o - p$ where D_a is atmospheric drought, p_o is the vapor pressure of pure water and p is the vapor pressure of air.

Table 1. Continued.

METHODS OF ANALYSIS (Cont.)

Reference	Concept
Jones (1966)	Jones uses Hamons potential evapotranspiration equation $$PE = 0.0055\ D^2\ P_t$$ where D is the day length factor and P_t is the saturation vapor density in grams per cubic meter at the daily mean temperature. Tables for D and P_t are given in Hamon's original paper. The equation is of value because it can operate at temperatures below freezing.
Askew, et al. (1971)	Generated monthly streamflow records are used to give a set of synthetic critical drought periods for the design and operation of reservoir systems.
Kates (1971)	Kates shows that natural hazards give rise to different choices of adjustments. He notes that hazard (drought) effects are a function of the size of the event and the character of adjustment. As an example of drought, he shows effects on health, wealth and population movement as well as adjustment to the drought. The model can be adapted to computer simulation.
Clyde and King (1973)	These authors recognize that all available water resources should be used in analysis of any system. A linear programming model of an economic-hydrologic-physical system is used to optimize various combinations of water use.
Kirkpatrick (1976)	Agriculture land (in Utah) uses about 3.73 acre-feet of water per acre. One urban acre of land in Salt Lake County utilized 3.2 acre-feet. Results show that the encroachment of urbanization upon agricultural lands should free water for other uses unstead of creating more demand on existing water supplies. Nothing is said of industrial uses.

Table 1. Continued.

METHODS OF ANALYSIS (Cont.)

Reference	Concept
Hiemstra (1976)	Hiemstra has modeled drought based on conservation of mass. The model is limited in area considered and is site specific. Parameters used include soil moisture, daily runoff, infiltration and evapotranspiration.
Bayazit and Sen (1976)	The authors model monthly streamflows using an autoregressive, integrated, moving average (ARIMA) model. By preserving "dry period" statistics, the run-length statistics of drought are generated.
Kavvas and Kelleur (1976)	From rainfall data, these authors calculate drought lengths and the return period of rainfall events for drought computations. They also calculate the marginal probabilities of drought lengths. The model used is adequate only for large areas.
Institute for Policy Research, Western Governors Policy Office (1977)	This group defines drought affected groups and sectors as well as associated problems and impacts in a very detailed analysis.

SPECIFIC DROUGHT INDICES

Reference	Concept
Goodridge (1965)	The drought index is defined which measures the relative magnitudes of extended periods with little or no precipitation. $$\text{Drought Index} = \sum_{\text{First dry day}}^{\text{Last dry day}} \text{Average value}$$ Each day of the year is weighted in accordance with its average daily rainfall. Probabilities of drought occurrence may be computed.

Table 1. Continued.

SPECIFIC DROUGHT INDICES (Cont.)

Reference	Concept
Magnuson (1969) and Palmer (1965)	Palmer's index treats drought severity as a function of accumulated weighted differences between actual precipitation and precipitation requirement. The index values can be correlated with general crop conditions, forest fire danger, water supplies and economic disruption. Index values are summarized by large areal climatic division.

CLASSES FOR WET AND DRY PERIODS

MONTHLY INDEX VALUE	CLASS
≥ 4.00	extremely wet
3.00 to 3.99	very wet
2.00 to 2.99	moderately wet
1.00 to 1.99	slightly wet
.50 to .99	incipient wet spell
.49 to - .49	near normal
- .50 to - .99	incipient drought
-1.00 to -1.99	mild drought
-2.00 to -2.99	moderate drought
-3.00 to -3.99	severe drought
≤ -4.00	extreme drought

Reference	Concept
Russell, et al. (1970)	An index of water system inadequacy is developed from a relation between potential demand and supply. Adjustment of water supply systems to drought conditions is also considered. Resulting estimates of costs and losses from water shortage as well as general rules of thumb for planning purposes are tabulated.
Kates (1971)	Kates' model considers human use modification adjustments, characteristics of human use, natural events, modification of natural events, adjustments, and hazard effects to derive a natural hazard system. This sytem combines the natural and human use system in a water-yield relationship.

Table 1. Continued.

SPECIFIC DROUGHT INDICES (Cont.)

Reference	Concept
Richardson (1977)	For climate comparison purposes, Richardson has devised a winter severity index and a summer severity index. These indices intend to use the same parameters of severity as those to which the user will relate human comfort. The Winter Severity Index is: $$W = 100 \left(\frac{100 - T_a}{68} + \frac{S_a}{75} + \frac{D_o}{90} \right)$$ where T_a is the sum of the average winter temperature for the three winter months. S_a is the sum of the average snowfall for these months and D_o is the sum of the number of days below freezing. Summer Severity Index $$S = \overline{T}_{max} + (0.057 - 0.0143\ T_R)(T_{max}-58)$$ where T_{max} is the sum of the maximum daily temperature and T_R is the daily temperature range.

daily river discharges. The probability of the daily smallest value is found using the third asymptotic distribution or theory of extremes. This method assumes that (1) n=365 is a large number and (2) daily streamflow values, while interdependent for a few successive days, are independent for large periods of time. As with flood problems, the return period and characteristic drought are calculated. There is no attempt to calculate drought duration or the areal extent of drought.

Yevjevich (1967) objectively defines drought as a deficiency in water supply. In his work, the theory of runs is used to define the duration, areal extent, beginning and ending of drought problems. The runs of a stochastic variable, or combination of stochastic and deterministic components, may be defined in various ways. In Figure 1, if an arbitrary value X_o is chosen, it cuts the series in many places. The relationship of X_o to all other values of X is the basis for the definition of runs. For a given sequence Xt and the selected base value X_o, the concepts of runs which may be used for practical objectives of series analysis are:

τ_1 - distance between upcrosses;

τ_2 - distance between downcrosses;

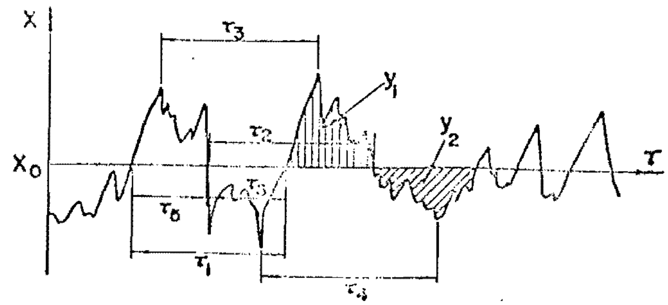
τ_3 - distance between successive peaks

τ_4 - distance between successive troughs;

τ_5 - distance between the successive upcross and downcross;

τ_6 - distance between the successive downcross and upcross;

γ_1 - sum of positive deviations between the successive upcross and downcross;



Source: Yevjevich, Vujica. 1967. An objective approach to definitions and investigations of continental hydrologic droughts. Hydrology Paper No. 23, Colorado State University. Fort Collins, Colorado.

Figure 1. An example of a series of the theory of runs

γ_2 - sum of negative deviations between the successive downcross and upcross

Some of the concepts of runs are as follows:

1. τ_1 - distance between upcrosses;
2. τ_2 - distance between downcrosses;
3. τ_3 - distance between successive peaks;
4. τ_4 - distance between successive troughs;
5. τ_5 - distance between the successive upcross and downcross;
6. τ_6 - distance between the successive downcross and upcross;
7. γ_1 - sum of positive deviations, between the successive upcross and downcross, and
8. γ_2 - sum of negative deviations, between the successive downcross and upcross.

For drought purposes, τ_5, τ_6, γ, and γ_2 are best suited in defining water shortage and duration. The τ_5 and τ_6, or distances between upcrosses and downcrosses represent the duration of drought conditions. The γ, and γ_2 are the sums of the deviations between the upcrosses and downcrosses. These sums of deviations represent the deficiency in water supply or the severity of drought. The theory of runs is easily adaptable to the Palmer Drought Index as well as the indices derived in this study.

Other definitions of drought are not used unless they specifically apply to the supply-demand concept. Russell, et al. (1970) was very useful in definitions of inadequacy, losses and adjustment of water supply systems to drought conditions.

There exists many types of drought definitions and regional drought indices as described above, but there exists no indices which specifically measure drought severity unique to a water supply system. In addition, the probability of water shortage at the present or in the immediate future and the probable degree of shortage are not measured. The purpose of this study is to develop a drought vulnerability index to indicate the probability of water shortage in a water supply system and to develop a drought severity index which will describe the state of a drought as it affects a water supply system.

CHAPTER III

METHODS AND PROCEDURES

Introduction

The purpose of this research is to develop relatively simple and practical methods for improving the availability of reliable information about droughts to those responsible for water supply management and planning. To accomplish this drought severity and vulnerability indices are developed for six pilot study areas. The indices and their delimitations are set forth. Physical descriptors, instrumentation, and data are described for each area. Methodological assumptions, limitations and evaluation procedures follow in this chapter.

Drought Indices

Two indices are developed to assess the severity of drought and the vulnerability of a water supply system to drought. Definitions for the two indices which are developed and tested in this study are:

1. Drought severity index, $S = \frac{U}{D}$ . . . . . (1)

$$= \frac{D - F}{D}$$

$$= 1 - \frac{F}{D} \quad . \quad . \quad . \quad . \quad (2)$$

where,

S = drought severity index

U = unfurnished demand, or the demand for water that is not capable of being filled because of drought related problems. It is also defined as the total demand (D) less the furnished demand (F).

D = total water demand, may be municipal demand (D_m) or irrigation demand (D_I)

F = furnished water demand, or the amount of water actually supplied to users during drought.

2. Drought vulnerability index, V(S') is the probability that the drought severity index (S) will exceed a critical value, S, and can be written:

$$V(S') = Pr\ (S > S') \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Drought severity index

The numerator and denominator in the definition of the drought severity index (Equation 1) are functions that vary over time. Therefore, S is also a function of time. The demand referred to in Equation 1 is the usual or forecast level of water demanded and does not reflect any reduction in demand due to conservation or regulatory measures implemented during a drought. These measures are reflected by the quantity of the unfurnished demand in the numerator of Equation 1. A "current" severity index (S_c) can be calculated to indicate the present status of a drought by using the current values for the unfurnished demand and the demand. Alternatively, severity indices can be calculated for different planning periods (S_p) using forecast values of demand and supply. For planning purposes the unfurnished demand as a function of time depends on both the drought conditions assumed and the operating policies considered for the water supply facilities.

Total demand (D) in Equation 1 is defined differently for municipal and irrigational considerations. In both cases it is necessary that the definition remain consistant so the resulting drought severity and vulnerability indices are comparable from location to location. With these definitions, it is assumed that the results of calculations of the drought severity index for the municipalities can be compared. The results of the calculations for the irrigation areas are also assumed to be comparable.

Furnished demand (F). Furnished demand is defined as the amount of water actually diverted for use by a municipality or irrigation area. The definitions, methods of calculation and data sources are found in summary form in Table 2. Historically furnished demand (F) is the measured diversion. For predictive or planning purposes, the furnished demand (F_f) is the forecasted diversion.

Municipal demand (D_m). For the municipalities, a demand definition is required that considers metered and unmetered systems, price of water, outside water use and population trends. These restraints enable the many differing municipalities to be compared on a consistant bases. This is accomplished using water demand functions developed by Hughes (1978). These demand functions represent a reasonably accurate and consistent method of calculating historical water demands as well as for predicting further water demands because:

Table 2. Summary of furnished demand (F) definitions, calculations and data for pilot study areas.

Pilot Study	Definition of Furnished Demand (F)	Method of Calculation of Furnished Demand (F) (Raw Data & Calculation Results Appear in Appendix)	Data Sources and Summary
Milford City	Total amount of water, in gallons, pumped from three city wells during a monthly period.	End-of-month well meter total readings in gallons are algebraically subtracted from the previous month's readings for each of the three wells. The resulting volume for the three wells are added together to obtain total city well pumpage for each month of record.	(Richards, 1977) monthly meter readings August 1967 through June 1977
Monticello City	Total amount of water diverted from spring and streamflow and treated for culinary use	Total monthly Monticello City treatment plant influence in million gallons as reported by King, et al. (1976)	(King, et al., 1976) monthly data January, 1966 through August, 1977
Orangeville City	Total amount of water diverted from streamflow and treated for culinary use	End-of-month city treatment plant influent meter readings are subtracted algebraically from the previous month's meter reading.	(Orangeville City 1977) daily meter readings November 1969 through June 1977
Milford Irrigation Area	Total amount of water reported as pumped for irrigation use in the Milford, Utah irrigation area.	Total area well pumpage data abstracted from the Water Commissioner's Report (Strong, 1977) and the State Engineers Office, State of Utah (1977).	(Strong, 1977 and State Engineers Office, State of Utah, 1977) Seasonal well pumpage 1958 through 1977
Oberto Ditch (Helper) Irrigation Area	Total seasonal canal diversions from the Price River, including flows from storage in Schofield Reservoir	Total seasonal diversion from the Price River including storage, as recorded by the Price River Commissioner and reported by the State Engineers Office.	(State Engineers Office, State of Utah, 1977) Seasonal diversions from Price River 1942 to 1976
Logan Irrigation Area	Total monthly diversions to the Logan, Hyde Park, and Smithfield Canal from the Logan River.	Total monthly diversions as measured at the Logan, Hyde Park, and Smithfield Canal head and published by the U.S. Geological Survey.	(U.S. Geological Survey, 1901-1977) daily and monthly records for water years 1901 to 1977.
Planning Study Logan Irrigation Area	Projected monthly diversions to the Logan, Hyde Park and Smithfield Canal from synthetic stream flow records produced for the Logan River.	Synthetic diversion data is generated by a sophisticated time series auto-regressive moving average model developed in this study for the Logan River and diversions to the Logan, Hyde Park and Smithfield Canal.	(U.S. Geological Survey 1901-1977) Synthetic monthly data generated for 200 years or 2400 months.

1. The systems included in the study are selected because of the quality, geographical location and representativeness of their flow measurements.

2. The measurements represent flow into distribution systems and not the sum of individual meter readings. Leakage, street cleaning and other necessary components of demand are included.

3. Differences in demand are adequately explained by price and an outside use index for both urban and municipal demands.

4. The data used in the study were obtained from the utility managers or measured by the study team in visits to the site and not from mailed questionnaires.

5. Statistical tests indicate high levels of confidence in the correlation for historical or predictive uses (Hughes, 1978).

Weaknesses and justifications of the demand function for use in the drought severity index include:

1. The multiple regression analysis from which the demand functions were determined were developed from monthly data for 14 systems for the three years, 1974, 1975, and 1976. The data for the systems was of good quality and the use of more than three years of data usually involves changes of price of water during the period.

2. It is recognized that demand does vary on a monthly and even daily basis. To calculate the monthly demand for each particular month requires more extensive data than is presently available. This work is presently being pursued but is not completed (Hughes, 1978). The monthly demand calculated from yearly averages provides a good first approximation for the drought severity index.

To compensate for this weakness and make the monthly demand more commensurate with the real higher summer demands as opposed to lower winter demands, a "monthly weight" is established. The monthly weight (M_w) is derived by summing furnished demand (F) over all months, summing over like months and taking the percent of like months to the total.

$$M_w = \frac{F_m}{F_t} \qquad (4)$$

where M_w = the monthly demand weight (dimensionless)

F_m = the sum of furnished demand for all like months (all January data, all February data, etc.)

F_t = the sum of furnished demand for all monthly data.

For example, Monticello City's furnished demand data is found in Table 3. The sum of all months furnished demand is 2130.27 million gallons. The sum of all January furnished demands is 110.70 million gallons. The monthly weight (M_w) for January demand is:

$$M_w = \frac{110.70}{2130.27} = 0.052$$

Monthly weight (M_w) is calculated in a similar fashion for other months for each municipality. These weights are tabulated in Table 4.

The parameters which represent the average municipal demand (D_m) were parsimoniously chosen from multiple regression results (Hughes, 1978). These parameters include price (cost) of water, number of water users and an index of outdoor use.

Table 3. Monticello City furnish demand (F), monthly treatment plant influent (million gallons)

	1966	1967	1968	1969	1970	1971
Jan.	11.81	8.56	6.44	6.40	9.36	8.62
Feb.	10.46	7.88	5.65	6.12	9.25	9.15
March	11.71	8.30	6.08	6.01	10.01	10.29
Apr.	16.32	10.73	8.39	14.02	9.32	18.22
May	24.36	23.44	22.38	28.09	20.78	21.14
June	26.34	18.96	23.88	24.53	27.84	27.34
July	20.96	19.53	24.31	29.87	30.71	27.46
Aug.	19.14	18.00	15.27	26.14	20.67	19.43
Sept.	12.97	15.50	20.50	22.75	15.05	16.29
Oct.	10.17	11.58	18.36	17.95	12.72	10.36
Nov.	9.33	6.92	12.37	8.18	10.62	9.18
Dec.	8.32	5.62	7.60	8.75	8.88	8.86
Total	181.89	155.02	171.23	198.81	185.21	186.34

	1972	1973	1974	1975	1976	1977
Jan.	9.26	9.41	10.00	9.48	12.37	8.99
Feb.	8.25	8.59	9.44	7.97	10.29	5.20
Mar.	15.00	9.74	12.08	9.21	10.79	7.19
Apr.	24.14	9.87	16.13	9.62	14.31	7.46
May	29.25	18.12	30.73	15.63	21.60	5.36
June	26.57	25.44*	32.90	30.84	30.00	5.26
July	27.03	32.08	21.92	23.72	29.58	7.57
Aug.	22.67*	28.51	16.15	24.21	25.63	8.39
Sept.	13.20*	21.96	10.04	20.70	17.67	--
Oct.	11.86	17.95	11.02	13.71	11.55	--
Nov.	9.54	14.48	9.46	11.61	9.73	--
Dec.	9.41	12.22	10.56	11.67	9.48	--
Total	206.18	208.37	190.43	188.37	189.21	67.8*

*Estimated

Table 4. Monthly weight (M_w) for pilot study municipalities.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Milford	.041	.037	.049	.068	.121	.140	.145	.144	.092	.077	.044	.043
Monticello	.052	.046	.055	.074	.122	.141	.138	.115	.088	.069	.052	.048
Orangeville	.122	.095	.079	.073	.097	.109	.086	.081	.060	.046	.053	.099

Costs of water were selected as those representing the water users perspective of what they are actually paying for water. Marginal costs are near \$0.20 per thousand gallons for the average system and average costs near \$0.83 per thousand gallons. Detailed analysis of costs and criteria may be found in the original work by Hughes (1978). The Drought Severity Index is calculated for each city for the price levels of \$0.20, \$0.50, \$1.00 and \$2.00 per thousand gallons.

The demand function is developed on a per person and per connection basis. For the study of small rural communities the use of the function on a per person basis is adequate. The demand function is represented by:

$$D_{md} = 40.75 + 30.54 \ln \frac{1}{P} + 24.14(I) \quad . \quad . \quad . \quad (5)$$

where

D_{md} = average demand of water per person per day

P = average cost in dollars per thousand gallons

I = outside use index (see Table 5)

Outside use is considered because of the great variation of this component among the Utah systems. A single, easy to use index is developed which accounts for the varied outdoor use demands. The index associates an integer between 1 and 9 with a category description, where index number 1 defines a system which provides no water for outside use, and increases in terms of outside irrigation to number 9, where all of the outside water use is furnished by the municipal system. Specific descriptions are shown in Table 5.

Table 5. Outdoor use classification index.
Source: Hughes, 1978

Categories Indicating Extent of Outdoor Demand from Domestic System
1. No outdoor use from domestic system--everyone has connection to pressurized dual system.
2. Almost no irrigation from domestic system--supplementary system is available which serves at least 85 percent of outside demand.
3. Supplementary ditch system is available and landscaped areas are very small.
4. No supplementary system is available but landscaped areas are very small.
5. Ditch system available for gardens but most lawns are irrigated from domestic system.
6. Ditch or piped system available to some customers but most outside irrigation is from domestic system.
7. All outside demand from domestic system--moderate amount of landscaping, average climate.
8. Large amount of landscaping and all from domestic system--average climate.
9. Large amount of landscaping and all from domestic system--hot and dry climate.

The resulting average demand functions are shown in Figure 2 as gallons per day per person. The Equation 5 expresses average demand as a function of the cost of water (P) and the outside use index (I). The correlation coefficient (R^2) for the equation is 0.805. The F test for significance, mean square ratio and a statistical significance discussion were adequate and may be found in the original work by Hughes (1978).

It has been the practice in planning studies to include a small growth trend in unit demand. Analysis of data over the last decade for systems in Utah do not support this concept (Kirkpatrick, 1976). Water use increases with outdoor demand and population growth, but demand per person has generally stabilized (Hughes, 1978). For these reasons, there is justification for using a stable average demand function to determine water demand for historical studies and for predictive (planning) purposes (Working, 1927). This provides a useful and consistent definition of demand for both metered and unmetered municipalities and which considers the major demand factors of outdoor use, price and population. Municipal daily demands (D_{md}) are tabulated in Table 6.

To calculate the monthly municipal demand (D_m) for use in the drought severity index, the municipal daily demand (D_{md}) is multiplied by the number of days per month, the monthly weight and the population estimate for a particular year for a city, or:

$$D_m = D_{md} \, d \, M_w \, P_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

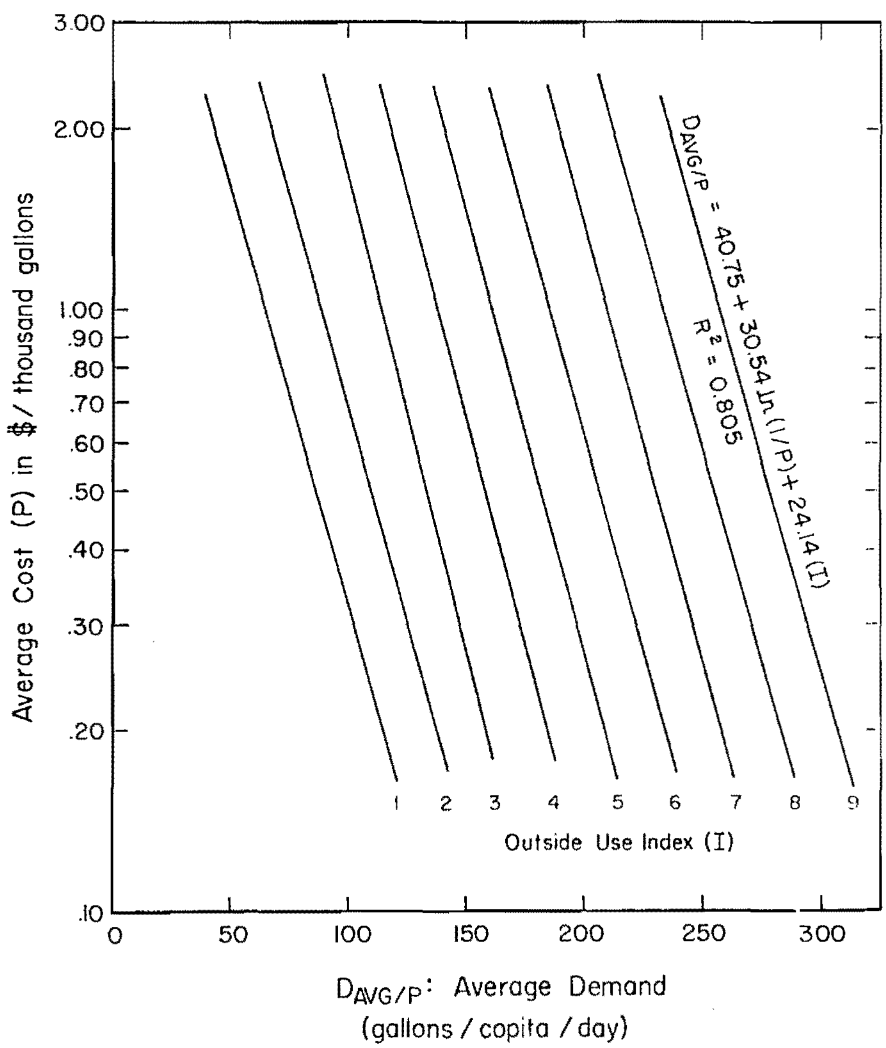


Figure 2. Municipal demand function.

Table 6. Daily municipal demand (D_{md}) in gallons per day per capita
$D_{md} = 40.75 + 30.54 \ln \left(\frac{I}{P} \right) + 24.14 (I)$

	Cost of Water				
City	$0.20	$0.50	$1.00	$2.00	Outside Use Index
Milford	209	237	258	279	9
Monticello	209	237	258	279	9
Orangeville	112	140	161	183	5

where

D_m = monthly municipal demand in gallons per capita

D_{md} = daily municipal demand in gallons per day per capita

d = number of days per year

M_w = monthly weight per year (dimensionless)

P_0 = population estimate, number of people.

For example, for the price of water at $0.50 per thousand gallons, the Monticello daily demand is 237 gallons per day per capita, the number of days in January is 31, the monthly weight is 0.052 and the population estimate for the year of 1975 is 1726. The municipal demand (D_m) is calculated for January as:

$$D_m = 237 \times 365 \times .052 \times 1726 = 7.76 \text{ million gallons}$$

Municipal Demand (D_m) is tabulated in the Appendix for the three communities for the period of record of study. Twenty-eight days were always used for the month of February.

The municipal demand (D_m) based upon the work by Hughes (1978), has many deficiencies. Some of these include:

1. The small number of communities and data used to derive the use rates.

2. The statistical justifications of the demand function.

3. The need for monthly and peak demand resolution.

Nevertheless, the author is convinced that the derivation of a demand function using the Hughes (1978) technique is the best practical way to define municipal demand that will be useable in models which vary over time and locality. As more data is collected the technique will be refined and the statistics will be improved. The method is assumed to be correct and the monthly weighting (M_w), though not a Hughes (1978) technique, is set forth as a good approximation of relative monthly weights until a corpus of data is collected with which monthly demands can be derived. The author assumes that the monthly demands (D_m) are valid as used in this study.

Irrigation demand. Irrigation demand (D_I) is defined as water that is diverted for farm irrigation purposes. This demand includes transmission requirements of the system, system losses and plant consumptive use. Consumptive use is defined as the amount of water transpired in the process of plant growth plus the water evaporated from soil and foliage in the area of the growing plant. Eight water requirement methods were examined (Ogrosky and Mockus, 1964, and

Veihmeyer, 1964), five methods critically (Appendix A), and the Blaney-Criddle method chosen as the most appropriate for this study. Reasons for this choice include:

1. The small amount of input data necessary,

2. Ease of useage

3. Parameters in the equation are easily obtainedd

4. Adaptability of the method to all locations within Utah

5. Estimates from the method have been found to be accurate (Sutter and Corey, 1970)

6. Wide acceptance of the method throughout the West

7. Close agreement to measured pan evaporation

8. The State Engineer for Utah uses the Blaney-Criddle equation to determine legal water requirements.

Assumptions made in using the Blaney-Criddle method for the computation of irrigation demand (D_I) include:

1. All factors other than temperature, length of growing season and percentage of daylight hours are similar from area to area.

2. Crops are not limited by drought conditions or lack of water at any time during the growing season.

3. Seasonal or monthly consumptive-use is proportional to the climate factor (8).

4. The crop coefficients (K), which have been determined experimentally (Veihmeyer, 1964; and Ogrosky and Mockus, 1964), do not fluctuate from area to area and can be assigned to a large general area.

5. The crop most widely grown in the three areas of study is alfalfa. Alfalfa is used as the base crop for this study.

6. The growing season for two areas is defined as the months April through September and as May through September for the Northern Utah area.

Seasonal consumptive use for a given crop is calculated by the Blaney-Criddle relation:

$$U = K_s B$$

or

$$U = K_s \Sigma \frac{tp}{100} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (7)$$

where

U = consumptive use of water in inches for the growing season

K_s = an empirical seasonal coefficient for a particular crop

B = the sum of consumptive-use factors for a given season

t = the mean monthly temperature in degrees Fahrenheit

p = the monthly daylight hours as a percent of the year.

For individual months the consumptive-use may be estimated by

$$u = \frac{k\ t\ p}{100} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (8)$$

where u is the monthly consumptive-use of water in inches and k, t, and p are the consumtive use values for that particular month.

A slight modification of the Blaney-Criddle method is made by the Soil Conservation Service (U.S. Department of Agriculture, 1967). This modification makes it possible to use crop growth stage coefficient values and mean monthly temperatures in lieu of the empirical monthly and seasonal crop coefficients tabulated in the literature (Ogrosky and Mockus, 1964). The crop growth stage coefficients are constant throughout the United States for each crop

(U.S. Department of Agriculture, 1967) and are tabulated in Table 7 for alfalfa for the growing season April through September. The monthly daylight hours (p) for the study areas are included in Table 8.

Table 7. Monthly crop growth stage coefficients for alfalfa (U.S. Department of Agriculture, 1967)

	Month					
	April	May	June	July	August	September
Monthly Crop Growth Stage Coefficient, k_c	0.99	1.08	1.13	1.11	1.06	0.99

Table 8. Monthly percent of daytime hours (p) (Interpolated from U.S. Department of Agriculture, 1967).

	Month						
Area	April	May	June	July	August	September	Seasonal Sum
Logan, Utah	9.98	10.11	10.22	10.33	9.61	8.40	57.65
Milford, Utah	8.90	9.92	9.99	10.13	9.49	8.37	56.80
Helper, Utah (Oberto Ditch)	8.92	9.99	10.07	10.20	9.52	8.39	57.09

The modification made on the monthly crop coefficient (k) is

$$k = k_c \, k_t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (9)$$

where

k_c = the monthly crop coefficient

k_t = the monthly climatic coefficient calculated by

k_t = 0.0173 t - 0.314, for values of monthly mean air temperature (t) from 36 to 100 degrees Fahrenheit.

It follows that the calculation of monthly consumptive use using the Blaney-Criddle method and the Soil Conservation Service modification can be written as

$$u = \frac{k_c \, k_t \, t_p}{100} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (10)$$

and the seasonal consumptive use can be calculated by summing the monthly consumptive use values for the season. For example, monthly and seasonal consumptive use values are tabulated in Table 9 below for the 1977 growing season for Milford, Utah.

Summing the monthly consumptive use values gives the seasonal consumtive use value

$$U = \sum_{i = \text{April}}^{\text{September}} u_i = 2.35 + 3.31 + 6.72 + 7.94 + 6.79 + 4.13 = 31.24 \text{ inches}$$

$$U = \frac{31.24}{12} = 2.60 \text{ feet}$$

where U = the seasonal consumptive use value.

Table 9. Calculation of monthly consumptive use (u) for Milford, Utah, for the 1977 growing season using the Blaney-Criddle method.

Month	t	P	k_t = (0.0173 T - 0.314)	k_c	$u=k_t\ k_c\ tP/100$
April	49.4	8.90	.541	0.99	2.35
May	52.3	9.92	.591	1.08	3.31
June	68.7	9.99	.866	1.13	6.72
July	73.6	10.13	.959	1.11	7.94
August	72.2	9.49	.935	1.06	6.79
September	63.4	8.37	.783	0.99	4.13

It has been noted (U.S. Department of Agriculture, 1967) that the portion of consumptive use that must be supplied by irrigation is:

$$D = U - R_e \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where

D = irrigation demand or the consumptive use supplied by irrigation

U = consumptive use as calculated by the Blaney-Criddle method

R_e = effective rainfall

The effective rainfall can be further defined as the amount of rainfall available to crops during the growing season. Since there are no records of effective rainfall available, it is necessary to estimate that portion of rainfall that is effective. Tables, graphs and methods are available to make this estimate (U.S. Department of Agriculture, 1967) based upon the assumption that there is a relationship between effective rainfall, mean monthly rainfall, average monthly consumptive use and a 3-inch net irrigation application.

For any particular crop in a certain location, monthly and seasonal consumptive use varies very little from year to year. On the other hand, effective rainfall varies widely from year to year. Demand based upon consumptive use less the effective precipitation can also be expected to vary widely. To make the irrigation demand used in the drought severity index more stable and less dependent upon meteorological probabilities, the effective rainfall is defined as insignificant during drought periods and Equation 11 becomes

$$D = U \qquad (12)$$

This definition is acceptable for this study because:

1. Drought is defined in this study in terms other than meteorological and verified by meteorological definitions (Palmer, 1965 and Richardson, 1977).

2. Future precipitation events and amounts cannot be predicted.

3. The establishment of effective rainfall frequency distribution for an area assumes that, all other factors being equal, effective rainfall will vary from year to year in direct proportion to the variance in total rainfall. Total rainfall is used as a measure of the frequency distribution of effective rainfall.

4. Precipitation intensity and duration are not considered.

5. During drought, precipitation events are few to non-existant.

6. Precipitation that does occur during drought usually occurs

in a few torrential downpours (Fletcher, 1977 and Goodridge, 1977). The effective precipitation amounts during these events is small.

7. Precipitation during "normal" or "wet" years will yield significant effective rainfall. This results in a decrease in the irrigation demand (see Equation 9) and a resulting decrease in the drought severity index (Equation 2). This decrease in effect, makes the already negative index more negative and has little bearing on drought severity.

8. Irrigation demand, defined in terms of consumptive use for an area, can be safely assumed to vary only slightly from year to year (U.S. Department of Agriculture, 1967) and provides a conservative and consistent concept of actual irrigation demand.

Because of the time and space characteristics of the irrigation areas in this study, it is necessary to make the following additional assumptions for irrigation demand:

1. Carryover soil moisture resulting from winter precipitation is assumed to be small from year to year.

2. Groundwater contributions (other than irrigation pumpage) are assumed to be small.

3. Soil temperature control with irrigation waters is assumed to be included in the irrigation efficiency (E) factor.

4. Leaching requirements are assumed to be included in the irrigation efficiency (E) factor.

As no convenient method exists for calculating transmission and loss requirements short of establishing a water budget, the writer assumes that these requirements can be estimated for particular localities by applying an irrigation efficiency (E) factor (Riley, 1978;

Sutter and Corey, 1970). For the Milford area, irrigation efficiency is assumed to be 60 percent (Griffin, 1978). In Oberto Ditch (Helper) area irrigation efficiency is 40 percent (Griffin, 1978) and historically, the areas served by the Logan, Hyde Park and Smithfield Canal Company, irrigation efficiency has been 50 percent (Haws, 1978). For planning purposes, future irrigation efficiency for the Logan, Hyde Park and Smithfield Canal area is also assumed to be 50 percent (Hill, 1978).

The average monthly irrigation demand (D_I) then is simply calculated as the consumptive use multiplied by the given acreage and that product divided by the irrigation efficiency for the area. The difference between the irrigation demand (D_I) and the total consumptive use for the given acreage represents the transmission and loss requirements of the system. For example, the seasonal irrigation demand for the Milford area in 1977 is calculated in acre-feet for 13,848 Acres and farm efficiency of 60 percent as:

$$D_I = \frac{UA}{E} = \frac{2.60\ (13848)}{0.60} = 60085 \text{ acre-feet} \quad . \quad . \qquad (13)$$

where

D_I = the seasonal irrigation demand in acre-feet

A = area irrigated in acres

E = farm efficiency (dimensionless)

The value 60085 acre-feet, is that amount of water that must be pumped from ground water supplies in order to meet crop, transmission and loss requirements for the 1977 growing season.

Range of the drought severity index

Equation 2 again is

$$S = 1 - \frac{F}{D} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

It should be noted that when $F >> D$, $S \simeq K$ where K represents a large negative value. When $F << D$, $S \simeq 1$ and when $F = D$, $S \simeq 0$. The drought severity index (S) is structured so that increasing positive values of the index relate to increasing drought severity. When the furnished demand (F) is equal to the demand (D), drought severity index (S) is equal to zero, representing an adequate water supply. As furnished demand (F) decreases, the ratio of furnished demand (F) to demand (D) also decreases and the drought severity index (S) ranges from zero to one. Positive S values imply a water shortage or drought. When the furnished demand (F) is greater than demand (D), the values of the drought severity index (S) are negative. All negative S values represent periods in which water supply is more than adequate.

Example calculations of the drought severity index (S). With the parameters of the drought severity equation defined, it is appropriate to show example calculations of the drought severity index. The drought severity index is written as

$$S = 1 - \frac{F}{D} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

For the City of Monticello, January, 1975, total municipal demand (D_m) is 7.76 million gallons. Furnished demand (F) is 9.48 million gallons. The drought severity index for the municipality then is:

$$S_m = 1 - \frac{F}{D_m}$$

$$S_m = 1 - \frac{9.48}{7.76} = - 0.22$$

which represents an adequate supply of water and no drought condition for the month of January, 1975.

The Milford irrigation area for the 1977 growing season has a total irrigation demand (D_I) of 60085 acre-feet of water. The furnished demand (F) for the area is 48229 acre-feet. Equation 2 for the irrigation season becomes:

$$S_I = 1 - \frac{F}{D_I}$$

$$S_I = 1 - \frac{48229}{60085} = 0.20$$

which represents drought conditions for the 1977 growing season.

Drought vulnerability index

The drought vulnerability index, V(S'), is the probability that the drought severity index will exceed a critical value, S'. For this study, the critical value (S') is assigned as zero, or the value at which furnished demand (F) is equal to total demand (D) (see Equation 2). Values above zero represent drought. Therefore, it is physically relevant to calculate the probability of exceeding the critical value of zero, or the probability of drought occurrence. Critical values can be set for any level of drought severity and their probabilities calculated in the same manner as those calculated here.

Pilot Studies

The pilot or case studies are divided into three major sections, each major section is separated into local area studies and each local area includes a physical description of the area, description of the instrumentation and data, data analysis and statistical analysis.

Municipal studies

Pilot studies of municipal water supply systems include:

1. Milford City, a small city in central Utah which relies totally upon pumped wells for its water supply.

2. Monticello City, in Southeastern Utah, which receives its water supply from springs, and

3. Orangeville City, in Eastcentral Utah, whose water is supplied by streamflow from Cottonwood Creek.

Milford City. Milford is located in Beaver County in the West-central Utah some 220 miles south of Salt Lake City. The city is situated in a flat to gently sloping valley which is 15 to 20 miles in width. Milford originally served as a railroad town but as the type and kind of railroad services have changed, the railroad is no longer the dominant factor of the economy. Presently cattle and sheep production, railroad services, mining and agriculture are the major economic factors influencing the area. The population of Milford as determined by the Bureau of Census (1977) was 1304 for the year 1970; 1337 for 1973; and 1283 for 1975.

The climate of Milford is well described in the climatological summary prepared by the National Weather Service (1977).

Milford is located in Beaver County in the west-central portion of the State. The City is situated in a flat to gently sloping valley 15 to 20 miles in width. The Mineral Mountains, 10 miles to the east of the station, and the San Francisco Range, 15 miles to the northwest, rise about 5,000 feet above the valley floor.

The station is in the Sevier River Basin, and drainage is toward the north. The Beaver River just to the east extends north-south through the valley, but no significant body of water is reached by it. The river is dry most of the time due to the low annual rainfall in the area, and to the Minersville Reservoir 6 miles east of Minersville, which regulates the flow of water in the stream. Water for the irrigation of agricultural land in the valley is obtained from the diversion of surface water from this reservoir and from numerous deep wells.

The climate is temperate and dry. The average annual precipitation is between 8 and 9 inches, and except for the irrigated land in the valley, vegetation is of the mid-latitude steppe type. Only one month, March, has a normal precipitation amount greater than one inch. Irrigation water is necessary for the economic production of most crops.

Snowfall is rather evenly distributed during the season. The snow is usually light and powdery with below average moisture content. January, the coldest month of the year, has the greatest average monthly total.

Relative humidity is rather low during the summer months. It increases considerably in the change from summer to winter, and winters are cold and uncomfortable.

Summers are characterized by warm days and cool nights. Temperatures of 100° or more occur about once in every two years. July is the hottest month with maximum temperatures on most days above 90°.

In four out of five years the temperature can be expected to drop to 10° below zero or lower; 28° below zero is the lowest reading ever observed at the station; the coldest ever recorded in the State is 50° below.

The average growing season is 128 days, rather short for a station near latitude 38° and at an altitude of 5,028 feet. This is due, in part, to the mid-latitude steppe type of climate which normally allows strong radiational cooling during the nighttime hours. The average date of the last freezing temperature, 32° or lower, in the spring is May 21, and the average date of the first freezing temperature in the fall is September 26.

> The longest and shortest growing seasons on record are 179 and 80 days, respectively. Considering long-term record, freezing temperatures have occurred as early as August 9, and as late as June 21.
>
> Diurnal heating is a factor in producing strong southerly winds during the spring and summer months. Winter winds may cause considerable drifting snow, with resultant hazards to stock and transportation in the area.
>
> Low pressure storm systems are rare during the summer months. Precipitation during this period occurs as showers or thundershowers and rainfall amounts from these storms are quite variable. As winter approaches, the number of atmospheric disturbances increases, reaching a maximum in the spring of the year. (p. 1)

Soils are generally unconsolidated sand, clay and gravel. Soil erodability is high (Erosion Control During Highway Construction, 1976). Permeability is moderately rapid and the soils have a water holding capacity of near 40 percent. The soils are highly alkaline.

Milford has water rights for eight wells. Of these wells, three are presently unused. Three other wells provide all of the culinary water for the city and the remaining two provide irrigational waters for the ball park and cemetary. There is also a one-family well at the airport which is owned by the Federal Aviation Agency (FAA) and provides 1.13 acre-feet per year.

The State of Utah, State Engineer's Office (1977) have the following recorded rights for Milford.

1. #C-13337, well no. 1 near City Shop, Size 16 inches and 14 inches, 467 feet deep, approved right of 1.114 cfs, 500 gpm, year around right.

2. #C-13338 and 13339, well No. 2 near 300 South and 100 West, Size 6 inches and 8 inches, 468 feet deep, approved right of 1.003 cfs, 400 gpm, year around right.

3. #A-18261, well No. 3 or Jakes Well, Size 14 inches, 504 feet deep approved right of 17.035 cfs, 763 gpm, year around right.

In addition, a year around culinary dual diameter well exists at the ball park which is 180 feet deep and has an approved right of 0.588 cfs or 265 gpm. The bottom portion of the well is 10 inches in diameter. The upper portion of the well is 12 inches in diameter. The water rights of this well include supplemental irrigation, which may not exceed 0.2088 cfs and is specifically designated for use on 37.8 acres at the fairgrounds. The city also has irrigation water rights of 40 acre-feet, for use on 10 acres associated with the cemetery. The cemetery well, a 7-inch well of 102 feet deep is approved to produce 0.5815 cfs during the April 1 through October 1 period. This water right is supplemental to the dual diameter well outlined above.

The source of water for Milford City is a large ground water reservoir directly beneath the city. The quality of the water is such that no treatment is necessary at the present time. The supply of water in the ground water reservoir is essentially infinite for municipal use in the area.

Monticello City. Monticello is located in San Juan County in southeastern Utah near the eastern foot of the Abajo (Blue) Mountains. This range, has peaks rising above 11,000 feet which are located almost directly west of the city. The terrain of the area is gently rolling and slopes toward the southeast.

The population of Monticello grew from 1431 in 1970 to 1726 in 1975. Growth from 1970 to 1973 was near 5 percent per year and from 1973 to 1976 only about 2 percent per year (U.S. Department of Commerce, Bureau of Census, 1977).

Future growth in Monticello depends upon activities in mining, agriculture and tourism. Development of oil and gas reserves will tend toward growth in petroleum distribution activities. Uranium is also a key factor in development. The future growth of Monticello will depend mainly upon resource development in the area. It has been estimated (King, et al., 1976) that Monticello's population should grow to 1900 by 1980, 2200 by 1990 and 2600 people by the year 2000. The population, of course, could increase much more rapidly if intensive resource development occurs.

The climate of the area is of the semi-arid or steppe type which has light precipitation, low relative humidities and large daily and annual ranges in temperatures.

There are four distinct seasons. Because of the altitude of Monticello (6980 feet MSL) the summers are normally pleasant. The average daily temperature ranges about 30 degrees Farenheit. The daily maximums are usually in the 80 degree range and the night minimums in the 40 to 60 degree range. Temperatures exceeding 100 degrees Farenheit are rare.

Winters are cold but usually not severe. Temperatures of less than zero seldom occur. Snowfall is generally light.

There are two separate rainfall seasons. One occurs during the winter months when Pacific storms frequent the region. The second occurs in late summer and early fall when moisture from the Gulf of Mexico moves into the region and develops as showers and thunderstorms.

Winds are normally light to moderate during all seasons.

Extremely strong winds and gustiness that occur are generally associated with thunderstorms.

The growing season, or freeze-free period, is about 120 to 140 days from the middle of May to mid-September (Ashcroft and Richardson, 1975). The principal components of agriculture production in the area are wheat, livestock and dairy products. Pinto beans are grown in a limited amount in the area east and south of Monticello (Richardson, 1977).

In 1939, the Blue Mountain Irrigation Company sold to Monticello the water rights for the culinary water system which was constructed in 1917. This sale included a one cubic foot per second (cfs) water right from Pole Canyon Spring, Bankhead Spring, Innes Spring, and the Copper Queen or Peachman Spring in the North Creek drainage. Monticello also obtained water rights to waters diverted from Potato Patch Spring, Gold Queen Spring, Abajo Spring as well as waters from Upper South Creek and Lower South Creek.

The combined flows from these springs and creeks are piped to two (50 acre-foot and 25 acre-foot) open reservoirs for storage. Excess flow from these two reservoirs is piped to another open reservoir to be used for irrigational purposes at schools and the municipal golf course.

The 50 acre-foot storage reservoir was constructed in 1974. Design was for 2:1 side slopes and an impermeable synthetic liner. Because funds were not available, the liner was not installed. Later a bentonite clay layer was applied as a sealer, but the reservoir still had leakage problems. The 25 acre-foot reservoir was constructed with a synthetic liner and is performing adequately. A propeller-type meter has been installed at the inflow to the storage system and daily records are available for the period from 1966 to the present.

Water from the storage system is treated and piped to a 500,000 gallon covered storage tank. The treated water is also metered. Storage in the covered tank is ignored because it makes up only about ten percent of the daily demand on the system. The system is entirely gravity fed and there are no pumps in the system.

The existing water storage is necessary because of the fluctuations in annual precipitation. As a result of the 1977 drought, the city is in the process of drilling five new wells which are expected to double the existing supply capabilities. One new well south of the city is expected to reach a depth of 1500 feet and produce 400 to 500 gallons per minute (gpm).

The residents of Monticello rely upon the city culinary supply system for household use as well as for lawn and garden irrigation. Furnished demand (F) defined as the amount of water treated for use. Historically there has been some spill after treatment but these amounts are insignificant when compared to monthly average demand. The furnished demand values for Monticello are found in Table 3.

Orangeville. Orangeville is located in southeastern Utah on the western edge of the Castle Valley. This valley is oriented northeast to southwest and is about 20-25 miles wide.

The city is surrounded by mountains, with the Wasatch Plateau rising immediately to the west to elevations more than 11,000 feet MSL. To the east, the Red Plateau rises some 7500 feet MSL.

The population of Orangeville in 1970 was 511, in 1973 it was 614 and in 1975, 655 residents inhabited the city (U.S. Department of Commerce, Bureau of Census, 1977).

The climate of the Orangeville area is of the semi-arid type. The major features of the climate are light precipitation, abundant sunshine, low relative humidity and relatively light winds. The four seasons are well defined with winters being cold and dry. Temperatures below zero every winter and at times even drop below -10 degrees Fahrenheit. The annual snowfall is normally light (Richardson, 1977).

Summer temperatures are relatively cool resulting from the elevation of Orangeville. Maximum daily temperatures are usually in the 80 degree range and the minimum temperatures in the 50 degree Fahrenheit range. Temperatures exceed 90 degrees infrequently.

The principal rainfall season is the summer and early fall when moisture from the Gulf of Mexico results in showers and thunderstorms. The surrounding mountain ranges are a definite contributing factor to the thunderstorms. In much of the valley area, August is the only month with precipitation exceeding 1 inch.

Winds are generally light to moderate in all seasons. In the spring time, when low pressure storms occasionally move through the region, strong southerly winds may blow for several days at a time. Extremely strong winds which rarely occur are associated with thunderstorms.

The freeze-free, or growing season is 120 to 140 days in length, extending from mid-May to mid-September (Ashcroft and Richardson, 1975). Farm production is based around livestock and livestock products. Wheat and hay are the most important agricultural crops.

The Orangeville City culinary water supply is taken directly from Cottonwood Creek. The water is treated, stored in a small (500,000 gallon) covered reservoir and then piped to the city residents. The amount of water treated daily is metered and recorded. The total amount of treated water each month for the 1969-1977 period is used in the drought severity index calculation as the furnished demand (F_m).

Irrigation studies

Pilot studies of irrigational water supply systems include:

1. Milford, Utah area, which includes the farm lands served by pumped wells for water supply,

2. Oberto Ditch area, near Helper, Utah, which farm lands receive water from storage facilities in Schofield Reservoir as well as surface runoff, and

3. Logan, Utah area, including the farm lands served by the Logan, Hyde Park and Smithfield Canal Company which has no water storage facilities and depends upon surface runoff.

Milford irrigation area. The Milford area and climate have been described in some detail under the Milford City discussion above. The area of groundwater pumping for irrigational purposes studied here lies south of the City. The unconsolidated materials underlying the valley contain the principle groundwater reservoir. This reservoir consists of three high-permeability zones separated by low permeability zones. Water pumped from the reservoir provide essentially all of the irrigation needs of the area.

The irrigation system studied is composed of 158 metered wells of various sizes and capacities in the Milford area. These wells are supervised by the Milford Water Commissioners and the records compiled are located in the State of Utah, State Engineer's Office in Salt Lake City, Utah. The system has records available from 1958 to the present.

One of the difficulties of administering a large irrigation area concerns problems associated with enforcing of the amount of water that can be pumped. In the Milford valley this criteria was originally set at 3 acre-feet of water per acre. This figure was later revised upward to 4 acre-feet per acre (State Engineers Office, State of Utah, 1977). The water must be used on the acreage for which it is legally appropriated.

A monthly accounting of the metered system was not obtainable. Only the irrigation season total pumpage was available. Though horsepower ratings, rate structures and well pump efficiencies were not included in the calculations, their inclusion in further studies should improve the resulting use values.

The furnished demand (F) is defined as the average pumpage for all of the irrigation wells for the particular irrigation season. The total demand (D) is the calculated demand using the Blaney-Criddle method described above.

The Oberto Ditch irrigation area. Helper is located in the northwestern area of the Price River Valley some 110 miles south and east of Salt Lake City, Utah. Helper is surrounded by steep mountains ranging between 9,000 and 10,000 feet MSL. The Wasatch Plateau rises 10 to 15 miles to the west of the city with peaks rising to over 12,000 feet.

The mountainous terrain has a significant influence upon the weather of the region, acting as a barrier to approaching storms. The weather and seasons are much like that of the Orangeville area. The climate is continental and dry with large ranges in daily temperature. Summer time maximum temperature sometimes reach 100 degrees and winters are cold and uncomfortable with minimum temperature reaching 15 to 20 degrees below zero Fahrenheit. The growing season averages about four months, extending from May through September.

The Oberto Ditch is a small canal that diverts water from the Price River. It was chosen for this study because: (1) records exist from 1942 to the present, (2) the canal has storage facilities in Schofield Reservoir, and (3) the number of acres irrigated is known. Monthly diversion records exist for the Oberto Ditch, but were not used. The reason for this is because it was not possible to separate the amount of water used which were previously stored in the reservoir and the flow of the Price River. The seasonal amounts used from the reservoir and Price River are available from records in the State Engineer's Office, State of Utah (1972). These records show 17 water right records on file for the Oberto Ditch. The total acreage shown for the rights is 50.12 acres. Five supplemental claims are filed above. Were these amounts totaled, they would sum to 66.84 acres, the amount of acres shown on the records for the 1942-1948 period.

The Logan irrigational area. The Logan area is located near the northeastern border of Utah in Cache Valley. The valley drainage basin covers about 1840 square miles. Although groundwater plays an important part in agricultural irrigation, it is the surface flows and drainage of the Logan River that are of concern in this study.

Logan River drains approximately 218 square miles. Average discharge near its entrance into the Cache Valley is about 285 cfs. The extremes of river flow range from a maximum of 2480 cfs to a minimum of 61 cfs.

Many canals have been constructed since the settling of the valley. These canals divert water from the Logan River for irrigational use. The construction of the Logan, Hyde Park and Smithfield Canal began in 1882 (Fifield, 1977). The object of the Canal Company was to divert waters from the Logan River at a high elevation so that the benchland on the east side of Cache Valley might be irrigated.

In the early 1900's dispute of priorities and water rights caused much contention. As a result, Judge James N. Kimball settled the disputes by decree. At flows above 367.9 cfs, the Logan, Hyde Park and Smithfield Canal Company can claim their full water right of 124.2 cfs (Haws, 1965). At 367.9 cfs and below, the Canal Company is required to share with other users on a proportional basis according to the Kimball Decree (Haws, 1965).

Although, population projections imply increases in Cache Valley in the future, these projections are of little value in this study.

The reason is because the amount of water available for use under the canal is specifically defined by water right and decree. The water right may be sold or transferred, but the existing water right may not be exceeded.

The climate of the Logan area is reflected in the following summary prepared by Richardson (1971) for the City of Logan:

> The city of Logan is located on benchland on the east side of Cache Valley in northern Utah. The valley is quite level, about 30 miles long and 10 to 15 miles wide. It is open to the north and is blessed with bountiful water resources including streams from the rugged Wasatch Mountains on the east and south. Bear River, which enters from the north, leaves the valley on its way to Great Salt Lake about midway on the west side between additional high ranges.
>
> Irrigation water to supplement natural precipitation is usually in abundance and plays a prominent role in placing Cache Valley among the leading dairy districts in the United States. Alfalfa is the chief crop supplemented by grains and other feeds. Sugar beets, canning peas, potatoes and many other items also play a vital role in the welfare of the valley.
>
> The Logan River skirts the southern edge of the City of Logan and, although the mountains rise abruptly to the east, flood hazards are not serious. Logan Peak, less than six miles away, towers 5,000 feet above the city.
>
> Winters are usually cold but not severe. The valley is sheltered somewhat from cold Canadian air masses by the blocking effect on the Continental Divide and other mountain ranges. Winter sports and outdoor activities are pursued avidly throughout the season.
>
> Spring is the wettest season of the year. Nearly 40% of annual total precipitation falls in March, April and May. Due to its low variability, a large degree of dependence can be placed on the seasons moisture supply. Only one year in ten receives less than two-thirds of the normal amount.
>
> Summer arrives rather abruptly the first part of June with warmer and drier weather. Extremes of heat or prolonged hot spells are virtually unknown. Mountains to the south and southwest and Great Salt Lake about 30 miles distant, help to deflect or moderate warm air currents from this quadrant. Nights are cool and humidity relatively

> low in the daytime. Maximum temperature of 100° or higher have been recorded only five times in the history of the station, the last time in July 1934.
>
> Crisp, cool weather ushers in the Fall season and frosts can be expected rather early, usually before mid-October. The earliest occurrence of freezing temperature or lower is September 15. Spring frosts, likewise, tend to linger on, which shortens the growing season. There is a 50% probability of freezing temperatures after the first week in May, and a minimum of 32° or lower has been recorded as late as June 12. (p. 1)

The water supply system for Logan, Hyde Park and Smithfield Canal Company consists of a canal that intercepts the Logan River in Logan Canyon approximately 3.8 miles east of Logan City. The canal is nearly 100 years old, and though frequent repairs have been made through time, the canal could be considerably upgraded and improved.

The furnished demand (F) is defined for this irrigation system as the total measured volume of water diverted monthly at the canal head. The demand (D) used in the severity index is the monthly consumptive use value for the growing season, calculated for the Logan, Utah area.

Irrigation studies for planning purposes

A pilot study is conducted for the Logan, Utah, irrigational area to develop a technique for projecting water supply characteristics and drought probabilities into the future.

In choosing a model to use in generating long-term synthetic streamflow data for planning purposes, many choices are available. Simulation techniques using models representing physical systems are very popular in operational hydrology (Fleming, 1975), but because of the large initialization requirements and the control of those requirements, makes use of this type of model impractical for generating long periods of synthetic data. Better is the use of a stochastic model which will retain the salient hydrologic properties of historical streamflow data. Models such as the Markov process, moving average process, fractional Gaussian noise and the autoregressive integrated moving average (ARIMA) process. From the standpoint of synthetic hydrology, the ARIMA processes are (a) simple to generate, (b) retain the characteristics of historical data, (c) can accommodate seasonality, trends and cycles, and (d) may be considered as approximations to fractional Gaussian noise (O'Connell, 1974, and Box and Jenkins, 1970).

The water supply chosen for this study is the Logan River near Logan, Utah. This stream has a seasonal, natural flow and excellent records have been maintained for over 80 years. Three small, run-of-the-river dams have been constructed on the Logan River and are in the order of 40 to 70 years in age. There is little control of the river. Figure 2 shows the seasonal variation of the stream for the Logan River from 1901 to 1977. The peak flows represent the snow-melt pattern associated with the warm temperatures of late spring and early summer.

Additional evidence of the seasonality of the stream is found in the autocorrelation pattern of the data. The autocorrelation of lag K is a method to measure the correlation of the data at K time units apart. The autocorrelation are dimensionless and take on values between +1 and -1. An autocorrelation value of +1 indicates that the data which have a common lag K and are perfectly correlated. A -1 demonstrates that there is a perfect negative correlation. Autocorrelation of 0 illustrates no correlation at a lag K.

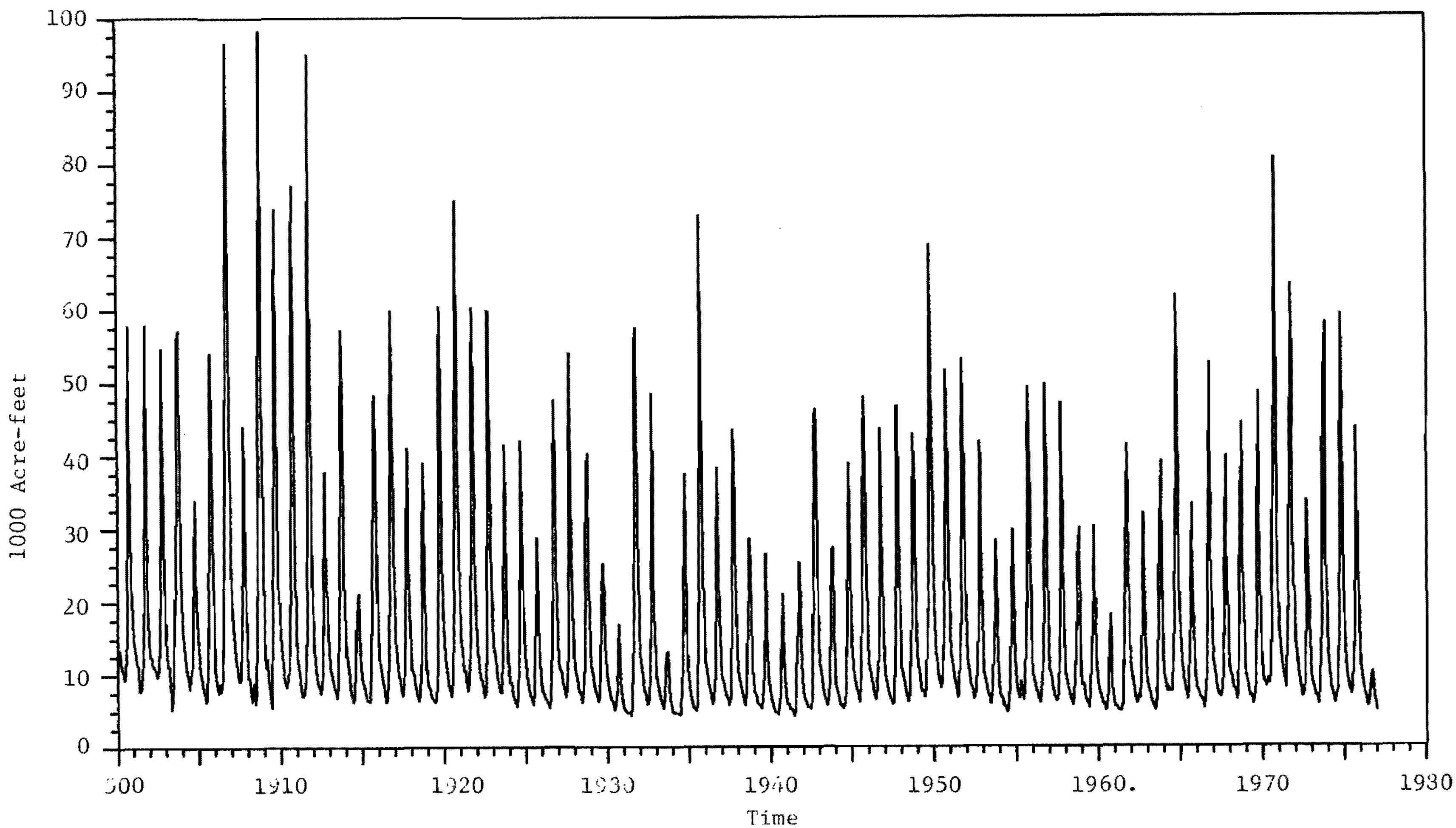


Figure 3. Time series of Logan River streamflow.

Figure 3 shows an example autocorrelation matrix and its resulting autocorrelation function. The autocorrelation equation is:

$$r_K = \frac{\sum_{t=1}^{N-K} (Z_t - \bar{Z})(Z_{t+K} - \bar{Z})}{\sum_{t=1}^{N} (Z_t - \bar{Z})^2} \quad . \; . \; . \; . \; . \; . \; . \; (14)$$

where:

r_K = the autocorrelation of lag K

N = the number of observations

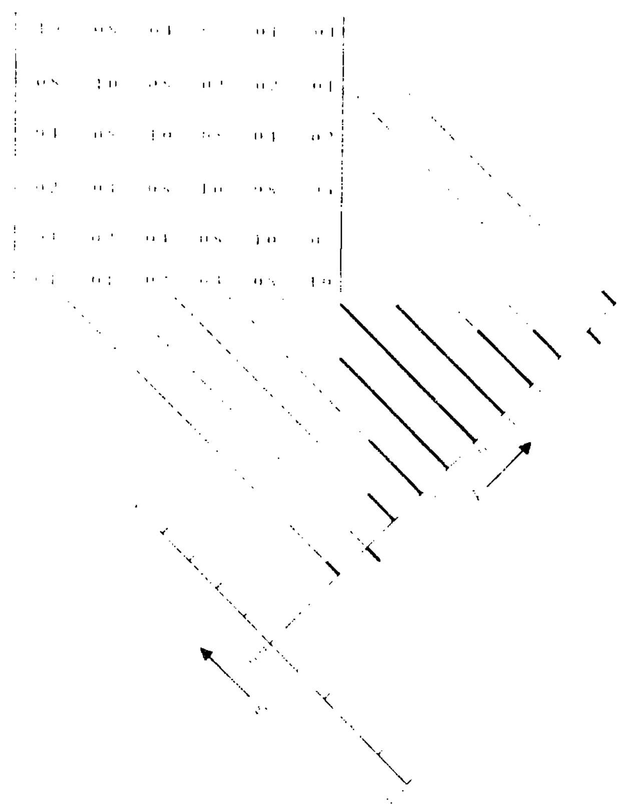
Z_t = the data value for month t

$\bar{Z}$ = the sample mean for the data (Z_t) values

K = the lag in time periods (months)

Figure 4 represents the auto-correlations of the monthly streamflow of the Logan River for 24 months. The strong positive and negative autocorrelations of the data are evident. The autoregressive nature of the data makes it possible to develop a model that adequately describes the data. Using the model developed, synthetic data can be generated that retain the statistical characteristics of the historical record (Ellis, 1977a).

To satisfactorily characterize streamflow the Box-Jenkins univariate time series methodology (Box and Jenkins, 1970; Nelson, 1973) is used. The general model has been used for business, economics, management science and industrial engineering applications. The model is now becoming popular in the fields of hydrology and water resources. Trends, seasonality, cycles and non-stationarity are accommodated by



Source: Box, George E. P. and Gwilynn M. Jenkins. 1970. Time Series Analysis Forecasting and Control. Holden-Day, San Francisco. p. 31.

Figure 4. An example autocorrelation matrix and its resulting autocorrelation function where ρ_k is the autocorrelation coefficient and k represents the lag.

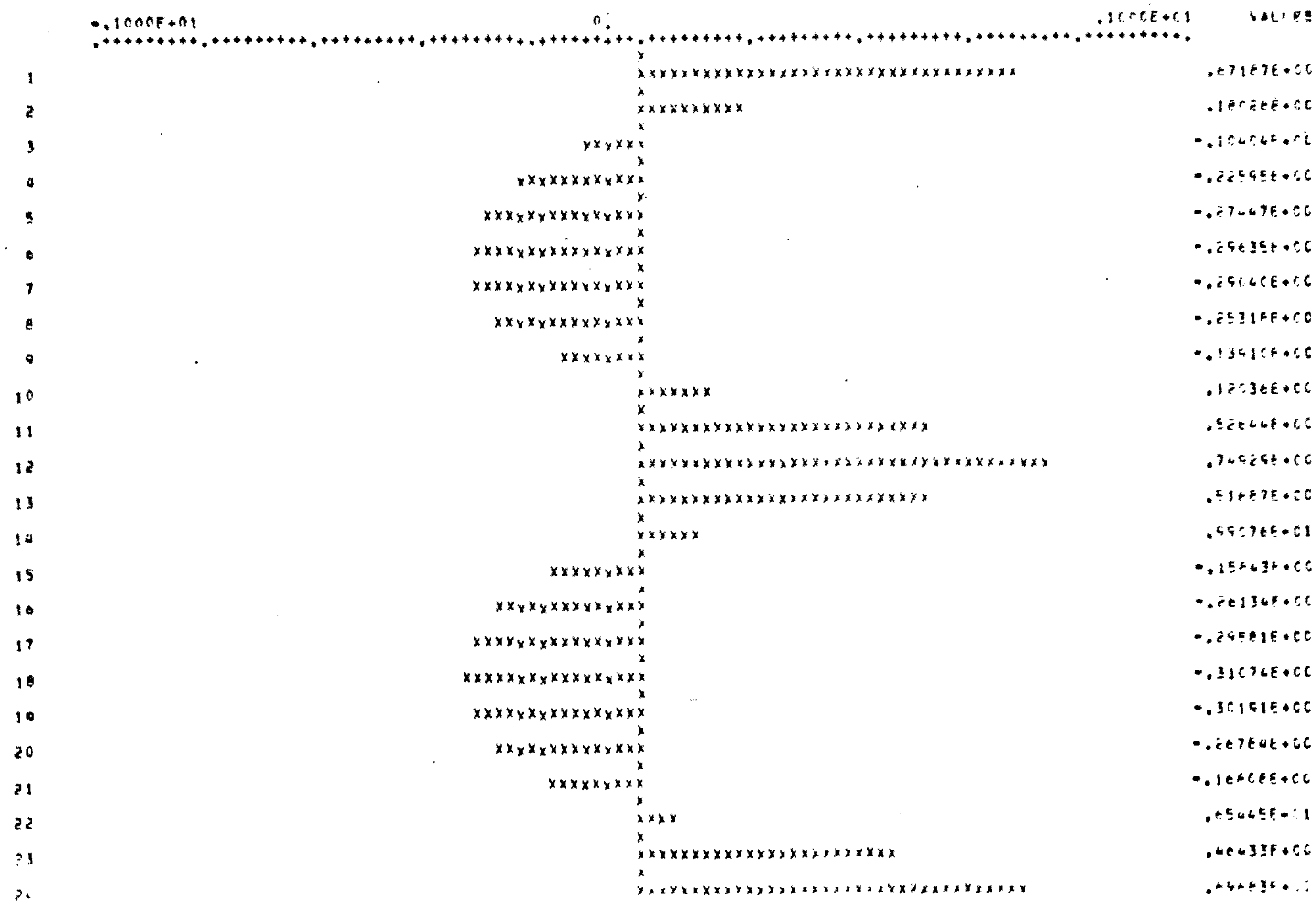


Figure 5. Autocorrelation of monthly streamflow for the Logan River.

the model. Therefore, assumptions need not be made about the characteristics of the time series. The model is instead adapted to fit the patterns of the time series. The general form of the model (see Box and Jenkins, 1970, Chapters 3, 4, and 9) is:

$$(1-\phi_1 B-\ldots-\phi_p B^p)\ (1-\phi_1' B-\ldots-\phi_p' B^{p'})\ (1-B^s)^{d_\ell}\ \dot{Z}_t =$$

$$\Theta_o + (1-\Theta' B-\ldots-\Theta_q B^q)\ (1-\Theta_1'-\ldots\Theta_q' B^q)a_t \quad \ldots \quad (15)$$

where

$\phi_i B^i$ = Regular autoregressive term for data auto correlations of lag i.

B = Backspace operator

$\phi_i B^i$ = Seasonal autoregressive term of lag i.

$(1-B^s)^{d_\ell}$ = a sequence of d_ℓ seasonal difference of period s.

$\dot{Z}_t$ = Z_t (the data value for the time period t) if d or d_ℓ is nonzero or $Z_t = Z_t - \mu$ if both d and d_ℓ are zero

μ = Series mean

Θ_o = A deterministic trend constant

$\Theta_i B^i$ = A regular moving average term of lag i for the residual error a_t.

$\Theta_i' B^i$ = A seasonal moving average term of lag i for the residual error a_t.

a_t = Random error or the residual error which affects the model at time $_t$.

The $(1 - \phi_i B^i)$ term is the regular autoregressive term for lag i and detrends steady monthly growth in the time series. The $(1 - \phi_i' B^i)$

term is the seasonal autoregressive term and detrends steady seasonal growth. The $(1 - B^s)^{d_\ell}$ term differences the data to stabilize seasonal data variations. The deterministic trend constant Θ_o, insures that the residual errors have a mean of zero in a non-stationary time series. The $(1 - \Theta_i B^i)$ and $(1 - \Theta_i' B^i)$ are the regular and seasonal moving average terms for lag i for the residual error a_t and are used to remove residual error patterns in the data.

The application of the methodology to the Logan River time series data requires:

1. Selecting the appropriate time series to be modeled.

2. Subjectively selecting a candidate model.

3. Estimating the parameters ϕ_i, ϕ_i', μ, Θ_o, Θ_i and Θ_i' using nonlinear regression analysis.

4. Diagnostic checking of the model for consistency and suitability.

Monthly time series data for the Logan River is readily available from 1901 through 1977. This period is represented by 924 monthly data points. In the interest of economy of time and resources, the 25 year period (300 monthly data points) from 1952 to 1977 is used. Three hundred data points are quite adequate for model development. To be certain that the data used is representative of the 1901 to 1977 period, a non-parametric ranking test, the "U-test," is used (U.S. Department of Agriculture, 1964). The U-test is a simple, distribution-free method of testing for the representativeness of sample data. To perform the U-test, the 924 monthly streamflows are ranked in decreasing order. The sum of the rank numbers (T_a) for the period 1952 to 1977 is 147,512. The number of data points in the period is denoted as a = 300 and the remaining number of data points as b = 624. The U-test statistic is calculated as

$$U = a\ b + \left[\frac{a(a+1)}{2} \right] - T_a = 84838 \quad . \quad . \quad . \quad . \qquad (16)$$

When the hypothesis that the distributions of the two periods are identical is true, the random variable (U) will have a normal distribution with the mean

$$\overline{U} = \frac{a\ b}{2} = 93600 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (17)$$

and variance

$$\sigma_u^2 = a\ b\ \left(\frac{a + b + 1}{12} \right) = 14{,}430{,}000 \quad . \quad . \quad . \qquad (18)$$

For the Logan River data, σ_u = 3798.68, and the statistic t is

$$t = \frac{U - \overline{U}}{\sigma_u} = -2.31 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (19)$$

the probability of a value of t greater than $\pm$ 2.31, with more than 120 degrees of freedom, is greater than 98 percent (Snedecor and Cochran, 1971). The conclusion drawn is that the 1952-1977 data for the Logan River has the same frequency and is therefore representative of the period 1901 to 1951.

The iterative procedure of selecting, estimating and checking is started with a simple model. For our purposes the model

$$X_t - \mu = a_t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (20)$$

is used as a beginning. The estimation of parameters is accomplished through the utilization of computer programs developed by Pack, et al.

(1972) and revised by Ellis (1977b). Diagnostic checking includes:

a. The standard deviation test. This is a test to see if the residual autocorrelations are within two standard deviations of zero (Ellis, 1977b).

b. The goodness-of-fit test. In an adequate model the sums of squares of the residual autocorrelations will have a chi-square distribution if the residual autocorrelations have a normal distribution with a mean of zero (Ellis, 1977a). If the residual autocorrelation of lag k is defined as r_k and N is defined as the number of data points remaining after all differencing in the model, then in equation

$$Q = N \sum_{k=1}^{K} r_k^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (21)$$

Q will have a chi-square distribution with (K-m) degrees of freedom, where m is the number of parameters included in the model.

c. Correlation Matrix of the Parameters. The off-diagonal values in the correlation matrix should be near zero if model parameters are uncorrelated with each other.

d. Overfitting. After obtaining an adequate model, a more elaborate model is fit which contains additional parameters in the direction of possible discrepancy. If analysis fails to show additions are necessary, then the model is "correct" (Box and Jenkins, 1970).

e. Parsimony. To be prodigal in the use of parameters leads to instability and inaccurate model parameter estimations. An adequate model is desirable that only includes necessary parameters (Nelson, 1973 and Box and Jenkins, 1970 , pp. 378-380).

Two adequate models are developed for the Logan River through this iterative procedure. For clarity, they are referred to as Model 1 and Model 2. Model 2 is written as:

$$(1 - \phi_1 B)\ (1 - B^{12}) Z_t = (1 - \theta_2 B)\ (1 - \theta'_{12} B^{12})\ a_t \quad . \qquad (22)$$

where parameter estimates are:

$\phi_1 = 0.70746$

$\theta_2 = 0.18135$

$\theta'_{12} = 0.79591$

The first 24 residual autocorrelations are within two standard deviations of zero as shown in Table 10. To test the goodness-of-fit, the value of Q_2 for Model 2 is 6.0137, with 21 degrees of freedom. A hypothesis that the residual autocorrelation is normally distributed with a mean of zero would not be rejected at the $\alpha = 0.995$ level (Snedecor and Cochran, 1971).

The correlation matrix of the parameters of Model 2 shows some correlation (0.5430) between parameter 1 (ϕ) and parameter 2 (θ_2). Other parameters are not significantly correlated. Overfitting and parsimony are tested in relation to Model 1.

		Parameter 1	Parameter 2	Parameter 3
Parameter	1	1.0000		
	2	0.5430	1.0000	
	3	-0.0611	-0.0287	1.0000

Figure 6. Model 2, correlation matrix of parameters.

Table 10. Model 2, autocorrelations of the residual errors.

Lags 1-12	0.00	-0.00	-0.02	0.00	0.02	0.00	0.00	-0.02	0.01	0.05	-0.01	0.01
Std. Dev.	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Lags 2-24	0.03	-0.01	-0.01	-0.00	0.01	-0.01	0.01	-0.02	0.02	-0.08	-0.08	-0.04
Std. Dev.	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06

Table 11. Model 1, autocorrelations of the residual error

Lags 1-12	0.07	-0.13	-0.00	0.02	0.03	0.01	0.00	-0.02	0.02	0.06	-0.01	0.01
Std. Dev.	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Lags 2-24	0.03	-0.01	-0.02	-0.00	0.01	-0.00	0.00	-0.01	0.02	-0.07	-0.09	-0.03
Std. Dev.	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06

Model 1 is written as:

$$(1 - \phi_1 B)\ (1 - B^{12}) Z_t = (1 - \theta_{12} B^{12}) a_t \quad . \quad . \quad . \qquad (23)$$

where parameter estimates are:

ϕ_1 = 0.63157

θ_{12} = 0.80365

The first 24 residual autocorrelations are found in Table 11 and only the second residual autocorrelation is slightly beyond two standard deviations of zero. For the first 24 residual autocorrelations, the value of Q for the chi-square goodness-of-fit test is 12.524 with 22 degrees of freedom. The hypothesis that the set of residual autocorrelations is normally distributed with a mean of zero would not be rejected at the α = 0.900 level (Snedecor and Cochran, 1971). The correlation matrix of the parameters of Model 1 in Figure 5 shows no significant correlation between the parameters.

		Parameter 1	Parameter 2
Parameter	1	1.0000	
	2	-0.0641	1.0000

Figure 7. Model 1, correlation matrix of parameters

Model 2 can be considered as a case of Model 1 which has been overfit. It is true that Model 2 does "fit" the time series data "better" when considering only the standard deviation and the goodness-of-fit tests described above. However, in Model 2 parameters 1 and 2 are correlated to some degree which raises the question if both are really necessary to model the time series. In addition, parsimoneonsly, Model 1 is a "better" model. In the interest of parsimony and realizing the very slight difference between the significance levels of the chi-square goodness-of-fit (α = 0.995 for Model 2 and α = 0.900 for Model 1), Model 1 is chosen as the model with which to generate synthetic streamflow data for the Logan River.

Model 1 (Equation 21) can be rewritten by using "backspace algebra" (Nelson, 1973) so that the data value, Z_t is a function of the previous data values and residuals.

$$Z_t = \phi_1 X_{t-1} - \phi_1 Z_{t-13} + Z_{t-12} + \theta_{12} a_{t-12} + a_t \quad . \quad . \qquad (24)$$

When the parameter values estimated from the historical time series are substituted in, the equation becomes:

$$Z_t = 0.63157\ (Z_{t-1} - Z_{t-13}) + Z_{t-12} + 0.80365\ a_{t-12} + a_t \qquad (25)$$

With the model in this form, synthetic streamflow values (Z_t) can be readily generated. This is accomplished by initializing the data values and choosing random error values that will be normally distributed with a mean of zero.

As noted in O'Connell (1974), after differencing the ARIMA process may be formulated as

$$Z_t - \mu_z = \phi_1(Z_{t-1} - \mu_z) + \sigma_z\sigma_a\ (a_t - \theta_{12}\ a_{t-1}) \quad . \qquad (26)$$

where μ_z and σ_z are the mean and standard deviation of the process. When the term a_t is an independent random variable with zero mean and unit variance, σ_a is defined by

$$\sigma_a^2 = \frac{(1 - \phi_1)^2}{(1-2\ \phi_1\ \theta_{12} + \theta_{12}^2)} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (27)$$

which insures that Z_t will have variance σ_z^2.

The data values (Z_t) for each month are initialized using the expected value of flow for each month. The error terms are initialized at zero to start the process. To eliminate any bias resulting from the initialization of the model in this manner, the first 20 years of generated monthly data (240 values) are removed, and only the following 200 years of synthetic monthly data are used to evaluate future drought conditions. These 200 years of synthetic data are tested against the 1952-1977 historical record (see "U-test" above). Results of the U-test are found in Table 12. The probability of a value of t greater than $\pm$ 16.03 or any of the other results, is greater than 99 percent and the resulting conclusion is that the synthetic data has the same frequency and is representative of the historical record. In addition, the mean and standard deviation for the historical period 1901-1977 are 16,071 and 14,468 acre-feet which compare well with the mean and standard deviation (16,071 and 14,476 acre-feet) of the synthetic 200 year record.

Table 12. Results of U-test. Synthetic data (a) in 50 year periods are tested against historical data (b).

	1st Period	2nd Period	3rd Period	4th Period
$\bar{U}$	90,000	90,000	90,000	90,000
σ_u	3676.28	3676.28	3676.28	3676.28
Ta	207,946	215,811	198,183	194,081
a	600	600	600	600
b	300	300	300	300
U	17,204	9,339	26,967	31,069
t	-19.80	-21.94	-17.15	-16.03

Because the synthetic values depend upon previously generated values (Z_{t-1}, Z_{t-12}, and Z_{t-13}) as well as the random error terms a_t and a_{t-12}, at times the synthetic Z_t value will be negative. Though negative flows are not permitted, the author believes that the generated negative values are important and should be considered. This is accomplished by replacing the negative flow value by a flow representing a streamflow recession from the previous month as

$$Z_t = \exp\ [\exp\{\ln[\ln(Z_{t-1})] - 0.025\}] \quad . \quad . \quad . \qquad (28)$$

where

Z_t = the value replacing the negative streamflow value

Z_{t-1} = the previous month's streamflow value exp = the exponential function, or exp = 2.71828

ln = natural logarithm function

0.025 = an empirically derived recession function.

For example, if the value for Z_t is negative, and the previous value (Z_{t-1}) is 9000 acre-feet, the new Z_t is derived as

$$2.184 = \ln(\ln 9000) - 0.025$$

$$Z_t = \exp(\exp 2.184) = 7188 \text{ acre-feet.}$$

Other values representing streamflow for the Logan River are used as generated.

With the synthetic streamflow data for the Logan River, the drought severity and the drought vulnerability indices may be calculated using the methodology adopted for the irrigation areas which rely upon the Logan, Hyde Park and Smithfield Canal. Historically, diversions to the canal from the Logan River during drought conditions have been based upon the Kimball Decree (Haws, 1965). This degree was adopted in 1923 to confirm existing water rights on the stream and to adjudicate streamflow among the many users. The decree has remained in force with minor changes. For the Logan, Hyde Park and Smithfield Canal Company, the decree allows diversion of 103.2 cfs on an 1860 priority water right and an additional 21.0 cfs on water right applications with a priority of 1928. The entity can divert the total 124.2 cfs at times when the Logan River flow exceeds 367.9 cfs. At flows below this amount the Canal Company may only divert a percentage of streamflow, according to Schedule A of the Kimball Decree as shown in Figure 7. In practice (Haws, 1978), the amount of water diverted by the water users of the Logan River is determined as

Revised Schedule "A"
Kimball Decree
Flow in Logan River

October 21, 1965

Award No.	Appropriations	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250
234	Logan City	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
216	Logan, Hyde Park & Smithfield	20.2	22.4	24.6	26.9	29.1	31.4	33.6	35.8	38.1	40.3	42.6	44.8	47.0	49.4	51.5	53.7
219	Logan Northern	22.9	25.4	27.9	30.5	33.0	35.5	38.1	40.6	43.2	45.7	48.2	50.8	53.3	56.0	58.4	61.0
224	Logan Hollow	0.6	0.6	0.7	0.7	0.9	0.9	0.9	1.0	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.4
220	Providence-Logan	3.2	3.6	3.9	4.3	4.6	5.0	5.3	5.7	6.0	6.4	6.8	7.1	7.5	7.5	8.2	8.6
	8th Ward Diversions	41.7	46.5	51.2	55.8	60.5	65.1	69.8	74.4	79.0	83.7	88.3	93.0	97.7	102.4	107.0	111.6
225	Logan Island	6.9	7.7	8.4	9.2	10.0	10.7	11.5	12.3	13.0	13.8	14.6	15.3	16.1	16.9	17.7	18.4
226	7th Ward	0.7	0.8	0.9	0.9	1.0	1.1	1.2	1.2	1.3	1.4	1.5	1.6	1.6	1.7	1.8	1.9
222	Hyde Park & Logan Northfield	14.8	16.5	18.1	19.8	21.4	23.0	24.7	26.3	28.0	29.6	31.3	32.9	34.6	36.2	37.9	39.5
227	Thatcher Irr. Co.	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.7	0.8
223	Logan Northwest Field & Benson	15.5	17.3	19.0	20.7	22.4	24.2	25.9	27.6	29.3	31.1	32.8	34.5	36.2	38.0	39.7	41.4
	Southwest Field	3.6	4.0	4.4	4.8	5.2	5.6	6.0	6.4	6.8	7.2	7.6	8.0	8.4	8.8	9.2	9.6
	Logan Cow Pasture	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
221	Providence-Pioneer	1.4	1.5	1.7	1.8	2.0	2.1	2.3	2.5	2.6	2.8	2.9	3.1	3.2	3.4	3.5	3.7
217	Hyrum Gibbons	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
	Power Rights																
	Utah Power & Light	69.8	77.6	85.4	93.1	100.9	108.6	116.4	124.2	131.9	139.7	147.4	155.2	163.0	170.6	178.5	186.3
	Central Milling	22.7	25.1	28.0	30.5	33.0	[illegible]	38.1	40.5	43.1	46.7	48.1	50.8	53.3	56.2	58.3	60.9
	Crowther Bros.	19.1	21.3	23.5	25.6	27.6	29.9	32.0	34.1	36.3	38.3	40.4	42.7	44.7	47.1	49.0	51.1

Cont., P. 2, Revised Schedule "A", Kimball Decree, Flow in Logan River

Award No.	Appropriations	260	270	280	290	300	310	320	330	340	350	360	370	380	390	400
234	Logan City	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
216	Logan, Hyde Park & Smithfield	56.0	57.3	59.5	59.5	70.8	75.3	79.8	84.3	88.8	93.3	97.8	102.3	103.2	109.3	116.0
219	Logan Northern	63.3	65.0	67.5	67.5	78.8	79.8	79.8	84.3	88.8	93.8	97.8	102.3	103.2	106.1	109.4
224	Logan Hollow	1.6	1.6	1.7	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.5	2.5	2.5
220	Providence-Logan	9.0	9.2	9.5	9.5	10.1	10.7	11.4	12.0	12.6	13.3	13.9	14.6	14.7	14.7	14.7
	8th Ward Diversions	116.3	119.0	123.8	123.8	128.4	128.4	128.4	128.4	128.4	128.4	128.4	128.4	136.4	137.4	137.4
225	Logan Island	19.2	19.6	20.4	20.4	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	20.9	21.4	21.4
226	7th Ward	1.9	2.0	2.1	2.1	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.0	2.0	2.0
222	Hyde Park & Logan Northfield	41.2	42.1	43.8	43.8	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	44.7	45.0	45.0
227	Thatcher Irr. Co.	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8
223	Logan Northwest Field & Benson	43.1	44.1	46.0	46.0	47.6	47.6	47.6	47.6	47.6	47.6	47.6	47.6	47.3	47.7	47.7
	Southwest Field	10.0	10.3	10.7	10.7	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	10.8	10.9	10.9
	Logan Cow Pasture	-	-	-	-	-	-	-	-	-	-	-	-	8.7	8.9	8.9
221	Providence-Pioneer	3.3	3.9	4.0	4.1	4.1	4.4	4.6	4.9	5.2	5.4	5.7	5.9	6.0	6.0	6.0
217	Hyrum Gibbons	.0	.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
P	Power Rights															
	Utah Power & Light	194.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
	Central Milling	63.3	63.9	66.2	68.5	70.4	70.4	70.4	70.4	70.4	70.4	70.4	70.4	70.4	70.4	70.4
	Crowther Bros.	53.1	51.6	55.5	57.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Source: Daines, Spencer H. 1966. Annual Report of Logan River Distribution System. State of Utah, Office of State Engineer. Logan, Utah.

Figure 8. Schedule A, Kimball Decree

a percentage of the total streamflow, regardless of the time of the irrigation season. These percentages for the Logan, Hyde Park and Smithfield Canal are:

a. 28.05 percent, when the Logan River flow is less than 367.9 cfs, but greater than 297.8 cfs,

b. 25.52 percent, when the Logan River flow is less than 297.8 cfs, but greater than 268.0 cfs,

c. and 22.39 percent, when the Logan River flow is less than 268.0 cfs.

It must be realized that actual diversions are dependent not only upon water rights, but upon canal capacity, recent rainfall, air temperatures, convenience of the water commissioner, politics, and many other factors as well. In addition, the water commissioner determines the distribution of the Logan River water on a daily basis. The actual percentages of monthly streamflow diverted to the Logan, Hyde Park and Smithfield Canal are found in Table 13 for the period 1931 through 1977. A water commissioner has been available from 1961 to the present to control the diversion from the river and therefore, it is expected that diversions during the period 1961 to 1977 are in accord with the legal requirements. It should be noted that the percentage of the Logan River flow diverted to the Logan, Hyde Park and Smithfield Canal is always less than the legal limit. Reasons for this include:

a. Aggregating diversions from daily to monthly averages masks short-term droughts of less than two weeks,

b. The actual carrying capacity of the canal is limited to the physical construction of the canal, which capacity may be less than the legal constraints,

Table 13. Percentages of Logan River diverted to the Logan, Hyde Park and Smithfield Canal.

MONTHS

		Apr			May			June			July			Aug			Sep	
Year	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
1931	1090	15230	14.27	4190	57860	24.94	2780	41090	23.76	1690	22190	22.84	1410	17830	22.52	1100	14690	20.91
1932	464	11900	3.05	4430	36360	8.22	6190	57910	10.77	7380	19450	24.12	3910	15130	23.55	1990	12380	15.92
1933	434	15030	4.30	1430	31820	5.86	7680	54680	15.84	4810	28060	25.86	2450	18940	19.60	2100	15000	21.56
1934	3090	22020	24.16	2850	56140	21.86	1940	57180	23.18	1240	34010	19.56	1050	21210	19.37	930	16320	19.58
1935	914	11420	8.16	3010	24170	10.21	6420	33970	17.12	4020	19860	23.77	1950	15430	17.76	1450	11780	17.51
1936	660	16400	2.71	5220	47200	7.16	6340	54000	12.30	6130	29300	25.84	3010	16500	19.31	2390	10800	20.31
1937	337	39600	3.37	4860	72400	12.65	5160	96500	16.51	4900	58100	27.37	2320	29400	18.88	1750	19800	18.44
1938	325	14900	1.65	3160	24500	7.27	6800	44100	16.77	4510	25000	22.99	2520	14500	18.57	1960	9520	19.14
1939	958	24700	5.67	5990	63600	20.90	4380	98300	23.99	2280	50500	19.02	1710	28900	18.51	1530	15100	20.51
1940	321	41300	3.23	6460	73800	24.41	3530	47200	22.09	2070	24100	20.39	1550	18100	19.87	1160	13500	17.74
1941	373	22800	5.28	4870	63500	23.14	3460	77100	21.98	1860	32100	18.98	1390	16900	18.91	869	12100	14.85
1942	87	16000	0.65	797	54600	3.94	6420	94900	25.25	2670	46500	19.36	1880	19600	19.69	1550	14900	20.89
1943	5	21400	0.02	4620	37800	10.13	3770	28500	8.12	6760	18100	25.91	3460	13400	22.99	2060	11100	18.18
1944	0	23000	0.00	2310	57300	8.66	2300	48400	8.41	3400	23800	22.25	1890	15300	17.71	1550	12600	18.97
1945	148	15100	2.03	2740	20200	9.81	3690	21100	9.48	6370	12500	27.01	2880	9650	20.15	1770	8440	16.06
1946	804	25800	2.41	5200	46100	10.83	6470	48400	16.51	5930	29600	27.14	3080	16500	20.91	1890	12200	16.71
1947	65	11900	0.51	3700	37200	8.49	4600	59900	15.20	4780	40500	27.60	2890	20200	23.21	1740	14900	17.83
1948	1	17300	0.01	2060	34900	4.39	5890	41100	12.76	6120	18700	29.09	3170	13600	22.68	2130	10600	19.61
1949	371	12700	1.99	3270	39000	7.62	5680	24100	17.14	4830	12700	26.32	2950	9830	22.66	2400	8540	22.14
1950	557	10900	2.60	1690	53200	3.44	6130	60400	8.91	6100	26300	15.24	4240	16000	21.42	2200	12600	15.35
1951	858	19500	3.15	1060	58800	2.05	6970	74900	15.10	6400	35900	25.82	3040	20700	18.84	2360	15300	19.06
1952	56	13600	0.28	3850	51100	7.24	6090	60300	13.25	6030	27000	26.80	3370	17800	22.27	1830	14500	15.51
1953	588	16200	5.04	2490	59900	11.51	4370	50600	10.43	5870	27800	26.71	2670	17600	19.78	1780	13800	17.50
1954	1330	19400	10.61	6360	41500	22.51	4200	21400	24.10	2430	13800	20.02	1670	10600	18.98	1070	8840	15.09
1955	22	15800	0.27	3190	42100	10.75	5570	30500	19.54	3140	18600	20.81	1960	12600	19.18	1170	10200	15.04
1956	1210	17700	5.35	4100	26700	8.33	5560	17100	13.26	4220	11600	22.30	2080	9060	16.56	1560	7720	16.22
1957	41	13900	0.37	1070	35800	3.17	4820	47600	9.70	6120	25000	25.97	2340	14900	17.06	1730	11500	16.62
1958	2	13900	0.02	4630	54100	9.81	5240	35200	13.46	4290	19100	24.33	2270	13400	18.35	1840	10600	16.76
1959	480	11200	3.81	4720	37400	18.37	5840	40300	19.51	3040	22200	20.39	2020	13700	19.39	1370	11100	16.31
1960	43	16200	0.27	4480	25200	14.87	5420	25100	24.00	2340	13900	18.57	1980	10500	21.22	1450	8460	18.66
1961	432	7640	5.87	4660	16800	25.83	3450	11700	23.78	1580	7400	19.36	1250	6260	19.75	948	5260	17.43
1962	545	15200	2.10	2840	53900	6.86	3230	57500	9.93	3740	30600	20.75	2300	16600	19.30	2190	12500	21.56
1963	52	10100	0.55	2990	24400	9.36	3790	48500	13.04	3250	18600	22.66	2160	12500	21.54	1420	9740	16.73
1964	209	12790	2.32	1900	13040	6.31	2090	8370	5.34	5050	6340	22.87	2530	5420	19.57	1660	4750	16.72
1965	190	11200	1.08	2790	29470	6.68	4230	37510	6.84	4830	16910	14.92	3490	10980	19.92	1540	8280	11.36
1966	341	24360	1.69	4400	72950	13.23	4520	51560	22.76	2510	23720	20.08	2140	15590	22.43	1680	11770	21.27
1967	0	10010	0.00	683	36410	2.65	2850	31260	5.42	4900	17900	17.28	3490	12290	22.63	2450	9490	20.89
1968	5	19650	0.05	2790	43450	9.94	3390	40540	6.52	4460	19620	21.41	2760	13570	19.73	1950	10240	18.16
1969	171	16890	0.86	3970	28660	8.95	3350	18260	11.83	4050	11990	21.95	2790	9240	23.04	2000	7460	20.70
1970	24	9940	0.29	1300	26550	3.88	3580	15980	7.37	5050	10150	22.49	3070	7800	22.98	936	6540	9.40
1971	266	7070	1.05	1530	21050	2.86	2800	15740	3.47	4560	9800	10.42	3360	7350	15.03	839	5850	5.18
1972	139	13390	0.57	3690	20230	6.67	4360	25430	6.89	5060	13790	16.65	4690	9550	24.88	2140	7420	14.97
1973	151	29360	1.61	2470	45600	7.34	4300	46440	14.15	5090	26090	29.98	3080	15050	25.80	1220	11330	12.84
1974	334	8760	1.97	3520	26660	6.94	4230	27360	7.28	5550	15280	20.53	4720	10670	28.43	3510	6170	27.32
1975	22	7280	0.28	616	27920	2.16	3490	38920	5.89	5420	23560	12.11	4900	14290	24.94	3810	11020	27.93
1976	58	33360	0.36	2320	48000	5.31	3640	39200	10.76	4700	21850	23.03	3150	14730	23.20	2810	11310	25.27
1977	1320	12770	16.97	2060	43590	20.32	1900	30270	19.65	1500	17320	22.16	1230	12450	21.43	1010	9760	20.74

A = Logan, Hydepark and Smithfield Canal diversion (Acre-feet)
B = Logan River streamflow (Acre-feet)
C = Percentage of Logan River flow diverted (percent)

c. Measurements of streamflow and canal diversions are subject to error (Dickinson, 1967).

In assuming that diversions to the canal will be the maximum allowed by the legal determinations according to the Logan River streamflow, is to assume that the physical conditions of the canal and streamflow measurements are perfect. Nevertheless, drought severity index calculations are made for these conditions and are found in Appendix B.

It is more reasonable to assume that the historical diversion percentages are representative of canal conditions and of the legal constraints. For the purposes of this study, the average percentage of flow actually diverted for use by the canal company, from 1961 to 1977 are used to compute the drought severity and vulnerability indices. Percentages where streamflow exceeded 21,224 acre-feet, were not used in the calculation. These average percentages and their standard deviations are found in Table 14. When the Logan River streamflow exceeds 22211 acre-feet month^{-1} (367.9 cfs), the Logan, Hyde Park and Smithfield Canal is assumed to be maximum as allowed by legal water rights; 124.2 cfs or 7498 acre-feet month^{-1}. When streamflow values are less than 22211 acre-feet month^{-1}, the monthly historical percentages of flow are used. The percentages are assumed to be representative of future diversions.

Table 14. Percentage of Logan River streamflow assumed diverted to the Logan, Hyde Park and Smithfield Canal when monthly flows are less than 22211 acre-feet.

	April	May	June	July	Aug.	Sept.
Percentage Mean	2.23	10.30	10.35	19.67	22.04	18.15
Percentage Standard Deviation	4.05	9.03	8.12	3.84	3.10	6.16

Statistical Analysis

Probabilities and distributions

In choosing the probability distribution of the drought severity index from which the probabilities are derived for the drought vulnerability index, the drought severity index values for each of the pilot study situations are analyzed in eight different probability distributions using computer programs created by Schmidt (1975) and McKee (1978). In order to fit the distributions with actual drought severity index values within the range of -4 to +1, some being equal to zero, a linear transform is necessary. The transform chosen is

$$S_n = S + 10 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (29)$$

where S_n is the transformed drought severity index, S is the calculated drought severity index and 10 represents the linear transform. The chi-square goodness-of-fit test is used to determine which distribution provides the "best fit" and that distribution is used to represent the distribution of the drought severity index for all study areas. The logarithmic-normal distribution was chosen as having the best fit for the drought severity index (see Table 16).

The drought vulnerability or probability of exceeding a critical value S' is calculated for S' = 0 or $S'_n = 10$ for the transformed data. This is done on the computer for the logarithmic-normal distribution function

$$f(x) = \frac{1}{x\,\sigma(2\pi)^{1/2}} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2\right] \quad . \quad . \qquad (30)$$

for the interval x = 10 to x = 11 for the transformed data. The logarithmic-normal mean and standard deviation as derived from the drought severity index data for each study area used in the distribution. As a check, the drought severity index distribution results are also plotted on logarithmic-probability graph paper and the results of both methods are tabulated in Table 16 in Chapter IV.

In addition, the probabilities of drought as related to the duration and extent of drought are calculated for one of the pilot study areas. This is done using the empirical distribution of the drought severity index values where the severity equals or exceeds zero ($S \geq 0$). The theory of runs (Yevjevich, 1967) is used to define the duration and extent of drought (see Figure 1). The probability of a particular duration of drought is calculated as the frequency of occurrence for that duration. For example, to obtain the probability that drought will have a duration of at least four months,

Table 15. Statistic parameters for the transformed drought severity index (S_n) values. Linear transform used is $S_n = S + 10$.

Study Area	Mean	Standard Deviation	Skewness Coefficient
Milford City			
at $0.20/KGAL	9.64	0.345	-0.049
0.50/KGAL	9.50	0.380	-0.065
1.00/KGAL	9.38	0.411	-0.082
2.00/KGAL	9.23	0.447	-0.106
Monticello City			
at $0.20/KGAL	9.98	0.265	0.005
0.50/KGAL	9.87	0.292	0.007
1.00/KGAL	9.78	0.316	0.009
2.00/KGAL	9.67	0.344	0.011
Orangeville City			
at $0.20/KGAL	9.895	0.275	-0.0164
0.50/KGAL	9.725	0.317	-0.0250
1.00/KGAL	9.558	0.359	-0.0365
2.00/KGAL	9.342	0.414	-0.0558
Logan, Hyde Park and Smithfield Canal			
Irrigation Season	9.555	0.323	0.0124
Monthly	9.526	0.698	-0.242
Milford Irrigation Area	10.167	0.086	-0.0003
Oberto Ditch Irrigation Area	9.996	0.542	-0.1818
Synthetic Logan, Hyde Park and Smithfield Canal			
Seasonal	8.040	3.979	0.04919
Monthly	7.726	1.369	-0.0225

Table 16. Results of transformed drought severity index (S_n) values in eight distributions

Study Area	Normal Distribution Chi-square	Normal Distribution Degrees of freedom	Normal Distribution Significance level	Logrithmic-Normal Distribution Chi-square	Logrithmic-Normal Distribution Degrees of freedom	Logrithmic-Normal Distribution Significance level
Milford City						
at $0.20/KGAL	6.085	2	0.048	7.27	2	0.026
0.50/KGAL	5.57	2	0.062	6.94	2	0.031
1.00/KGAL	6.50	2	0.039	8.12	2	0.017
2.00/KGAL	6.44	2	0.040	8.28	2	0.016
Monticello City						
at $0.20/KGAL	8.35	4	0.080	7.34	4	0.119
0.50/KGAL	7.90	4	0.095	6.82	4	0.146
1.00/KGAL	7.39	4	0.117	6.08	4	0.193
2.00/KGAL	8.71	4	0.069	7.29	4	0.121
Orangeville City						
at $0.20/KGAL	4.37	3	0.224	4.93	3	0.176
0.50/KGAL	4.44	3	0.218	5.128	3	0.162
1.00/KGAL	4.82	3	0.185	5.73	3	0.125
2.00/KGAL	4.74	3	0.191	5.83	3	0.120
Logan, Hyde Park and Smithfield Canal						
Irrigation Season	0.829	2	0.660	0.708	2	0.702
Monthly	20.73	5	0.0009	27.47	5	0
Milford Irrigation Area	1.571	0	0	1.60	0	0
Oberto Ditch Irrigation Area	3.73	2	0.154	4.79	2	0.091
Synthetic Logan, Hyde Park and Smithfield Canal						
Seasonal	22.587	5	0.000405	19.111	5	0.00183
Monthly	81.136	8	0	105.154	7	0

Table 16. (Continued.)

Study Area	Gamma Distribution Chi-square	Gamma Distribution Degrees of freedom	Gamma Distribution Significance level	Beta Distribution Chi-square	Beta Distribution Degrees of freedom	Beta Distribution Significance level
Milford City						
at $0.20/KGAL	6.54	2	0.038	6.99	2	0.030
0.50/KGAL	6.06	2	0.048	6.53	2	0.038
1.00/KGAL	7.08	2	0.029	7.68	2	0.021
2.00/KGAL	7.12	2	0.028	7.78	2	0.020
Monticello City						
at $0.20/KGAL	7.63	4	0.106	7.12	4	0.130
0.50/KGAL	7.13	4	0.129	6.58	4	0.159
1.00/KGAL	6.44	4	0.169	5.78	4	0.216
2.00/KGAL	7.69	4	0.103	7.00	4	0.136
Orangeville City						
at $0.20/KGAL	4.79	3	0.187	5.22	3	0.156
0.50/KGAL	4.94	3	0.175	5.45	3	0.141
1.00/KGAL	5.46	3	0.141	6.08	3	0.107
2.00/KGAL	5.49	3	0.139	6.24	3	0.100
Logan, Hyde Park and Smithfield Canal						
Irrigation Season	7.24	2	0.696	0.654	2	0.721
Monthly	26.81	5	0.00006	31.02	4	0
Milford Irrigation Area	1.598	0	0	1.623	0	0
Oberto Ditch Irrigation Area	4.08	2	0.130	4.38	2	0.112
Synthetic Logan, Hyde Park and Smithfield Canal						
Seasonal	19.66	5	0.00144	17.518	5	0.003615
Monthly	4.37	7	0	132.134	7	0

Table 16. (Continued.)

Study Area	Rayleigh Distribution Chi-square	Rayleigh Distribution Degrees of freedom	Rayleigh Distribution Significance level	Gambel Distribution Chi-square	Gambel Distribution Degrees of freedom	Gambel Distribution Significance level
Milford City						
at $0.20/KGAL	470.83	2	0	20.84	2	0
0.50/KGAL	408.31	2	0	19.33	2	0
1.00/KGAL	465.28	4	0	21.35	2	0
2.00/KGAL	409.13	5	0	21.41	2	0
Monticello City						
at $0.20/KGAL	799.30	3	0	6.38	3	0.094
0.50/KGAL	702.83	3	0	6.72	3	0.081
1.00/KGAL	623.76	3	0	6.26	3	0.099
2.00/KGAL	594.00	5	0	6.06	3	0.108
Orangeville City						
at $0.20/KGAL	466.99	1	0.0579	21.95	3	0
0.50/KGAL	377.86	1	0.0579	21.92	3	0
1.00/KGAL	354.82	2	0	22.85	3	0
2.00/KGAL	281.81	2	0	22.83	3	0
Logan, Hyde Park and Smithfield Canal						
Irrigation Season	180.07	0	0	1.64	2	0.439
Monthly	333.87	7	0	107.05	4	0
Milford Irrigation Area	423.06	-1	0	4.921	1	0.084
Oberto Ditch Irrigation Area	67.40	0	0	7.57	1	0.064
Synthetic Logan, Hyde Park and Smithfield Canal						
Seasonal	605.011	7	0	9.29	5	0.098
Monthly	451.27	9	0	213.86	6	0

Table 16. (Continued.)

Study Area	Pearson Type III Distribution Chi-square	Degrees of freedom	Significance level	Logrithmic-Pearson Type III Distribution Chi-square	Degrees of freedom	Significance level
Milford City						
at $0.20/KGAL	5.80	1	0.074	6.06	2	0.048
0.50/KGAL	5.23	1	0.080	6.89	2	0.032
1.00/KGAL	5.97	1	0.072	8.25	2	0.016
2.00/KGAL	5.80	1	0.739	8.06	2	0.018
Monticello City						
at $0.20/KGAL	8.27	3	0.004	NA		
0.50/KGAL	7.80	3	0.005	NA		
1.00/KGAL	7.25	3	0.006	NA		
2.00/KGAL	8.53	3	0.036	NA		
Orangeville City						
at $0.20/KGAL	4.25	2	0.119	NA		
0.50/KGAL	4.25	2	0.119	112.09	4	0
1.00/KGAL	4.54	2	0.103	4.40	4	0
2.00/KGAL	4.32	2	0.153	6.09	3	0.107
Logan, Hyde Park and Smithfield Canal						
Irrigation Season	0.81	1	0.405	NA		
Monthly	13.54	4	0.008	26.99	5	0
Milford Irrigation Area	1.54	-1	0	NA		
Oberto Ditch Irrigation Area	3.22	1	0.131	4.66	2	0.097
Synthetic Logan, Hyde Park and Smithfield Canal						
Seasonal	21.05	4	0.00308	17.63	5	0.0034
Monthly	89.34	7	0	104.83	7	0

Table 17. Results of logarithmic-normal distribution functions and drought probabilities, using transformed drought severity index (S_n) data

Study Area		ln-Mean	ln-Standard Deviation	Resulting Computed Probabilities	Resulting Graphical Probabilities
Municipalities and Price of Water					
Milford	$0.20	2.26537	0.0366943	.155093	.13
	$0.50	2.25094	0.0410828	.104185	.07
	$1.00	2.23769	0.0451622	.075174	.05
	$2.00	2.22200	0.0500687	.053533	.03
Monticello					
	$0.20	2.29984	0.0265509	.458716	.43
	$0.50	2.28938	0.0295143	.327170	.28
	$1.00	2.27987	0.0322666	.240595	.21
	$2.00	2.26851	0.0354967	.168406	.15
Orangeville					
	$0.20	2.29165	0.0281714	.348867	.30
	$0.50	2.27426	0.0331345	.196221	.23
	$1.00	2.25673	0.0382018	.114894	.10
	$2.00	2.23352	0.0451967	.063106	.03
Irrigation Areas					
Logan, Hyde Park and Smithfield Canal					
Seasonal		2.25650	0.0336878	.085642	.09
Monthly		2.25122	0.0757532	.222448	.29
Milford Irrigation Area					
		2.31906	0.00850273	.977275	.94
Oberto Ditch Irrigation Area					
		2.30074	0.0562726	.444794	.40
Synthetic Logan, Hyde Park and Smithfield Canal					
Seasonal		2.08329	0.0486761	.000003	.01
Monthly		2.02804	0.1854850	.046340	.00

the number of occurrences where the drought severity index equalled or exceeded zero for at least four months are calculated. This total of occurrences is then divided by the number of four-month periods to obtain the desired probability.

To obtain the extent of drought, the sum of the positive drought severity index values are calculated between successive upcrosses and downcrosses (Figure 1) and the frequency of these sums determined. The frequencies are found by dividing the sums of the positive drought severity index values by the total of the positive and negative sums.

The distributions and resulting probabilities for duration and extent can be determined by the same procedure as used to determine the distributions and probabilities of the drought severity index values. The paucity of data describing the duration and extent of drought limits this study to one empirical example.

Evaluation Procedures

It is necessary to verify that the drought severity index indicates drought at various levels of severity. To accomplish this the drought severity index is compared with the Palmer Drought Index (Magnuson, 1969; Palmer, 1965 and Richardson, 1977). The drought severity index is valid only for drought conditions for particular water supplies in Utah. The Palmer Drought Index is a regional meteorological index for both wet and dry periods which was meant for use in the agricultural areas of the mid-western United States. Hence, the two indices, aimed at different goals are not expected to compare exactly, but during years of extreme drought both indices should indicate drought. As an additional check, drought consequences as they affect public opinion about water generally and agriculture specifically, are measured by counting the number of related articles that appeared in a regional, daily newspaper for the 1958-1976 period. Again, while not being a direct index of drought consequences, the frequency of articles appearing in the newspaper are compared with the drought severity index.

Table 18. Drought Articles, General (Utah) SL Tribune

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Sum
58								1	1				2
59	7	1	3	2	3	6	4	4		1	5	1	37
60	1	2	3	4	2		6	6	3	3	3	1	34
61	4	9	11	13	10	5	10	5	4	3	3	7	84
62	1								1		1		3
63	5	5	9	8	3			2	4	1		1	38
64		1	1	3	1			1	2		1		10
65													0
66				3			4				1		8
67													0
68											1		1
69						1		1					2
70													0
71													0
72													0
73		3	1			1							5
74					1			3	1	1	2	1	9
75	3	1	1	1			1						7
76									2			1	3

Table 19. Drought Articles Under Agriculture SL Tribune

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Sum
58							2						2
59						1	1			5		3	10
60							1	1	3	3			8
61		1	1		1	1	1	1	1	1	1		9
62											1		1
63				2	2			1					5
64				2	1			1					4
65													0
66						1	3	2		1			7
67													0
68													0
69						2							2
70													0
71								1					1
72					3	6	3						12
73													0
74							4	3	3	3	1		14
75													0
76										1			1

CHAPTER IV

RESULTS AND DISCUSSION

Introduction

The overall objective of the research is to develop relatively simple and practical methods for improving the availability and reliability of information about droughts to those responsible for water supply management and planning. To achieve this objective a drought vulnerability index and drought severity index are developed and tested. For planning purposes, synthetic water supply data is generated and evaluated using the same methods developed for the historical water supply data.

This chapter contains four sections. The first and second sections include the results, discussion and comparisons for the three municipalities and the three irrigation areas. In the third section, the planning application, results and discussion are set forth. The last section contains statistical analyses and application techniques of the methodology.

Municipality Results and Discussion

Background

Three small municipalities, Milford, Monticello and Orangeville, Utah, are chosen to test the drought severity and vulnerability indices. The objective of the study is to calculate the drought indices for each city and evaluate the indices in light of the Palmer Drought Index and public opinion of drought conditions as found in daily newspaper articles.

Municipal demand (D_m) for the calculation of the drought severity index is defined in a similar fashion for each community. The demand function (see Hughes, 1978 and Chapter III above) is determined for the four prices $0.20, $0.50, $1.00 and $2.00 per thousand gallons for the municipalities. The only differences in the calculation of the municipal demand (D_m) are in population size and outside use index. Furnished demand (F) is defined as the amount of water used each month as determined from water treatment plant records or well pump records. The drought severity index is calculated from these parameters for each of the four prices of water for each community.

The drought vulnerability index, or the probability of water shortage in the immediate future, is determined from the drought severity index values. The probability of the drought severity index equaling or exceeding the value where furnished demand equals the municipal demand ($S \geq 0$) are calculated for each community at the four prices of water noted above.

In all cases, the historical water supply record as well as the calculated drought severity index value are included in Appendix B. Graphical plots of the drought severity index for the different prices are included with the discussion of each municipality. A comparison of the results for the three communities is also included.

Milford City

Milford City is located in west-central Utah and the climate is generally hot and dry. Culinary water in Milford is priced such that all residents pay the same rate each month regardless of the amount of water used. Water is pumped from ground-water supplies as needed and there is a small storage (310,000 gallons) facility. The total amount of pumped water each month is considered in this study as furnished demand (F). Municipal demand (D_m) is calculated using estimated population values and an outside use index of 9 (see Chapter III). The drought severity index values for Milford are found in Figure 9. The drought vulnerability, or probability of water shortage in the immediate future is calculated and included in Table 20.

Milford City has an almost unlimited supply of groundwater. There are legal constraints as to how much water can be pumped, but if user demand for water increased, the additional water rights could be obtained. Milford has no metering of individual dwellings and the result is that the average use rate (397 gallons per day per capita) is higher than that of similar communities (Kirkpatrick, 1976). The infrequent occurrence of drought conditions, shown in Figure 7 as periods when $S \geq 0$, is explained as:

1. The result of the large supply of groundwater available on demand of the user,

2. The actual cost of water (in this case pumping and maintenance costs) are borne by all water users on an average cost basis, and

3. The demand function was derived from cities having metered systems.

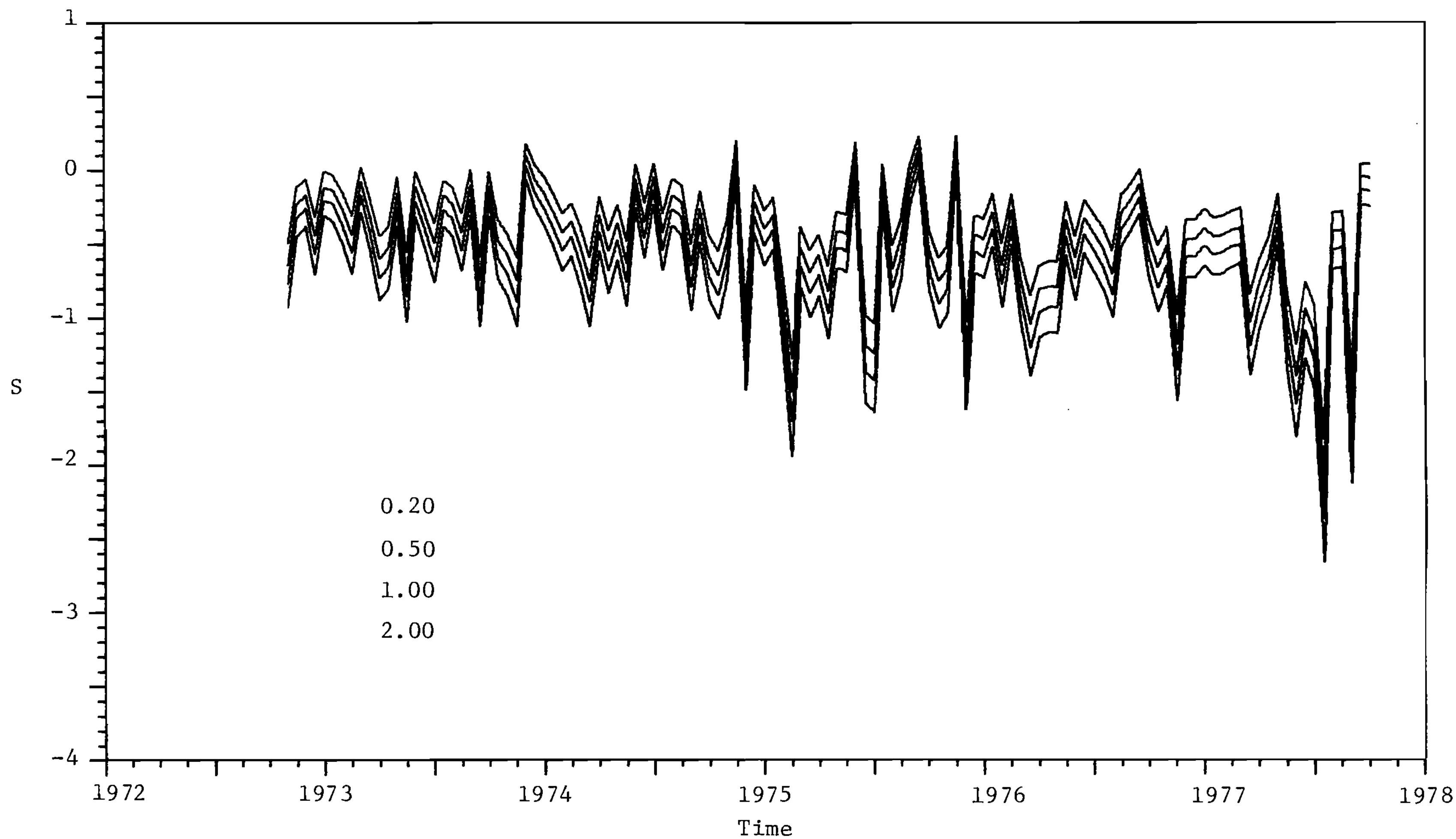


Figure 9. Drought severity index values (S) for Milford City.

Table 20. Drought vulnerability index for four water prices for Milford City, Monticello City and Orangeville City, Utah.

City	Price of Water (dollars/thousand gallons) $0.20	$0.50	$1.00	$2.00
Milford	15.5	10.4	7.5	5.4
Monticello	45.9	32.7	24.1	16.8
Orangeville	34.9	19.6	11.5	6.3

The results imply that the city, even during present drought conditions in surrounding areas, is not experiencing water shortage and there is only a 15.5 percent probability or less that they will experience water shortage in the immediate future.

In comparing the drought severity index with the Palmer Drought Index for moderate drought conditions (less than -2.00) and newspaper articles that appeared in the Salt Lake Tribune, the years 1973 and 1977 stand out as drought years (see Table 18). Years such as 1975 appear to have experienced less severe droughts, while years such as 1968-1971 have little or no drought problem.

There appears to be agreement among the indices during years of no drought conditions, but little agreement among them for drought conditions.

Monticello City

Monticello, is located in southeastern Utah. The climate is hot and dry and residents rely entirely upon the city water supply for culinary and outside lawn and garden irrigation. Given the historical

Table 21. Occurrence of drought comparisons of drought indices for Milford City, Utah.

Year	Drought Severity Index $0.20	Moderate Palmer Drought Index	Number of Newspaper Articles
1968	0	0	1
1969	0	0	3
1970	1	0	0
1971	1	0	0
1972	1	5	0
1973	4	0	5
1974	0	4	9
1975	1	2	7
1976	0	1	3
1977	2*	6*	**

*Only January-June considered

**Not available

city water treatment plant record and the historical population estimates, the municipal demand (D_m) and furnished demand (F) are calculated as discussed in Chapter III. From these parameters the drought severity index is calculated for the 1966-1977 period of record. Drought severity index values are plotted for Monticello and may be found in Figure 10. Drought vulnerability index values for the four prices are found in Table 17 above.

Monticello water users are metered on an individual basis and it is expected that the municipal demand function relates quite well to actual user demand. It should be noted that at low water prices

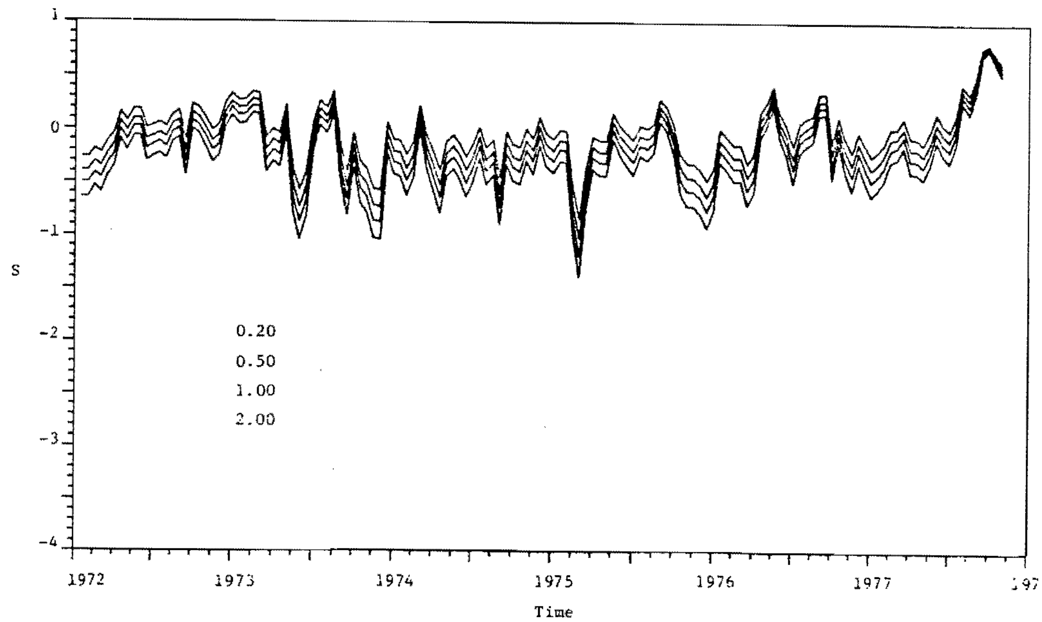


Figure 10. Drought severity index values (S) for Monticello City.

($0.20 per thousand gallons) the probability of water shortage in the immediate future in 45.9 percent and that even if the water price was raised to $2.00 per thousand gallons, a ten-fold increase, the probability would be decreased to only 16.8 percent.

For comparative purposes, the drought severity index is tabulated in Table 22 with the moderate Palmer Drought Index for the southeast region of Utah and newspaper articles appearing in the Salt Lake Tribune. In years 1973, 1974, 1976 and 1977 drought conditions are evident. For years 1967-1969 drought conditions are shown in the drought severity index, but the tendency does not exist in the other indices. The sum of drought severity values for the

Table 22. Occurrence of drought comparisons of drought indices for Monticello City, Utah.

Year	Drought Severity Index $0.20	Moderate Palmer Drought Index	Number of Newspaper Articles
1966	5	0	8
1967	9	1	0
1968	6	0	1
1969	4	0	2
1970	1	0	0
1971	2	2	0
1972	2	6	0
1973	5	4	5
1974	5	3	9
1975	5	0	7
1976	5	2	3
1977	8*	8*	**

*Only January through August considered
**Not available

1967-1969 period is 3.86 units while the sum of the first 8 months in 1977 is 4.33 units. Comparing these values shows that the 1967-1969 drought period as shown in the drought severity index is "mild" in comparison to the present drought. Also, it should be noted that in the 1967-1969 period Monticello was loosing population at a rate between 3 to 5 percent each year, which may be an indication of unaccounted for parameters. In all, the author feels that the drought severity index compares well with the other indices and is a good indicator of drought in Monticello. An additional factor to indicate the severity of the 1977 drought, is that the City of Monticello has begun drilling four new wells which will double the water supply for the city.

Orangeville City

Orangeville is located in central Utah near Price, Utah. Because it is located in the energy development area, it is expected to experience rapid growth. The community water supply is taken directly from Cottonwood Creek, treated and supplied to the residents. The City also has a secondary irrigation water supply that is used for lawn and garden irrigation. The municipal demand function describes the municipal demand for the city with an outside use index of 5. The amount of water treated monthly constitutes the furnished demand (F). Drought severity index values for Orangeville are found in Figure 11, and drought vulnerability indices are found in Table 17. At a price of $0.20 per thousand gallons, the probability of water shortage in the immediate future is 34.9 percent, which can be expected to be reduced to 6.3 percent by increasing water prices to $2.00 per thousand gallons.

In comparing the drought severity index and the test indices, it can be seen in Table 23, the agreement between the Palmer Drought Index and the drought severity index in all years except 1975. This is expected because the Palmer Drought Index measures meteorological drought, and meteorological conditions affects streamflow directly. Drought conditions in 1975 are in agreement between the newspaper articles index and the drought severity index. In rechecking the

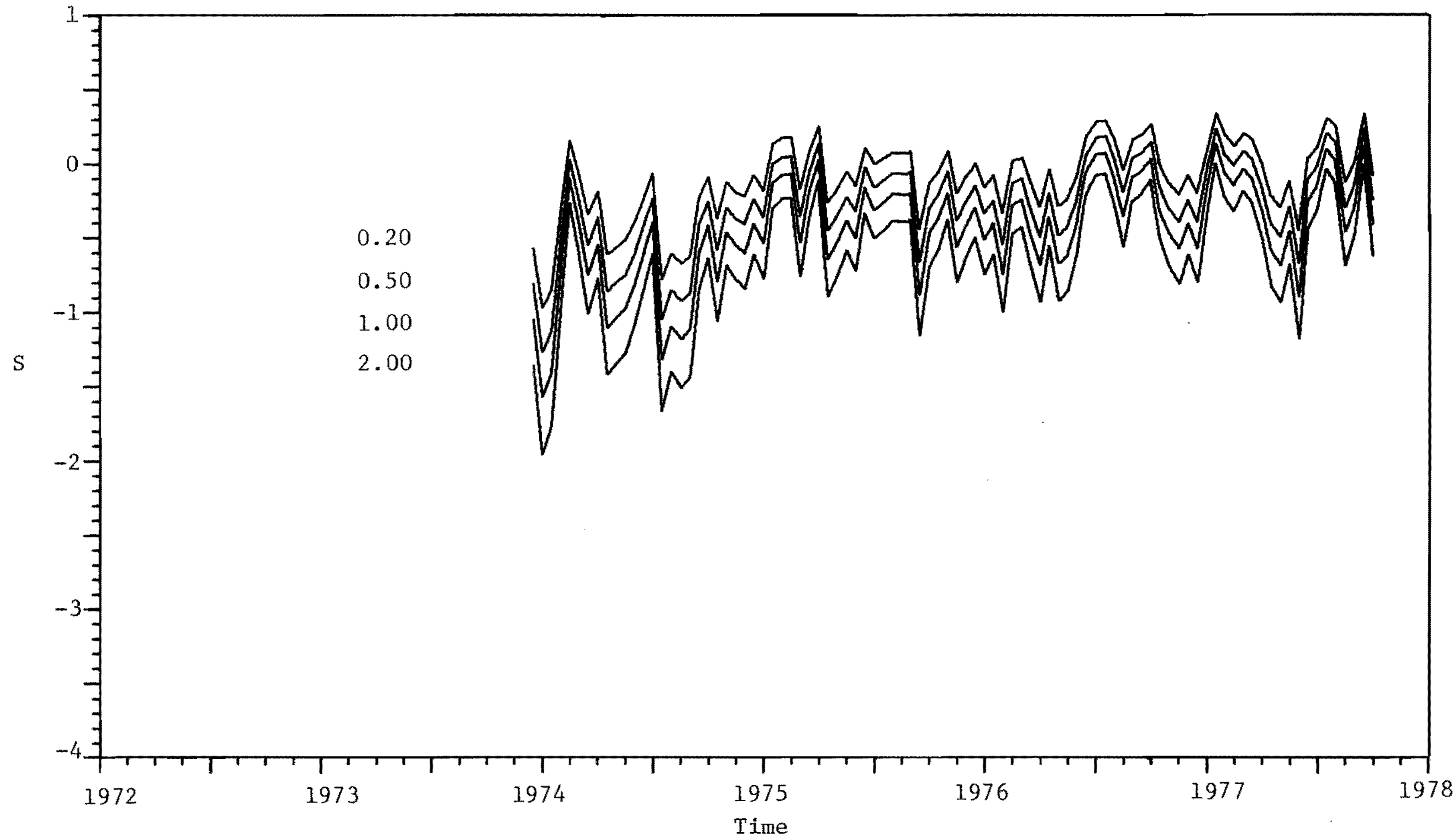


Figure 11. Drought severity index values (S) for Orangeville City.

Table 23. Occurrence of drought comparisons of drought indices for Orangeville City, Utah.

Year	Drought Severity Index $0.20	Moderate Palmer Drought Index	Number of Newspaper Articles
1970	1	0	0
1971	0	2	0
1972	6	6	0
1973	6	4	5
1974	3	3	9
1975	5	0	7
1976	6	2	3
1977	4*	6*	**

*Only January through June considered
**Not available

Palmer Drought Index for 1975, it is found that the Palmer Index recorded mild drought conditions (0.0 to -1.24), but the six monthly values were not significant enough to record as drought for comparison purposes.

Comparing the results of the municipalities

Having discussed each municipality separately, a comparison is made among the values of the drought severity index and the drought vulnerability index. Table 24 shows the drought severity indices comparisons for years common to the three communities. Because of similarities of the drought severity index characteristics, the comparison is made for the price of water at $0.20 per thousand

Table 24. Drought occurrence and severity sums, for Milford, Monticello and Orangeville, Utah. Water price is $0.20 per thousand gallons.

	Yearly Drought Occurrences			Yearly Drought Severity Sums		
Year	Milford	Monti-cello	Orange-ville	Milford	Monti-cello	Orange-ville
1970	1	1	1	.04	.21	.16
1971	1	2	0	.20	.12	0
1972	1	2	6	.19	.18	.96
1973	4	5	6	.55	.59	.38
1974	0	5	3	0	1.02	.27
1975	1	5	5	.01	.96	1.09
1976	0	5	6	0	.31	1.07
1977*	2	6	4	.09	2.98	.92

*For the period January-June only

gallons only. In addition to drought occurrence, the sum of the drought severity values are also included for comparison among the cities.

To compare, for the year 1971, each city experienced one period of drought, but it was most severe in Monticello and least severe in Milford. In the drought year of 1973, Monticello experienced five periods of drought whose total was more severe than the six periods at Orangeville. During 1977, Monticello is most severely affected by the drought conditions, and given the drought vulnerability indices found in Table 17 above, that city is also most vulnerable to drought. Figures 9, 10, and 11 also graphically show this condition.

Because each of the municipalities drought severity and vulnerability indices are derived using the same demand function and similar furnished demand information, a regional water supply planner can make decisions about the effect of drought on a community. Were a decision necessary in granting loan applications to increase water supply at the three communities, the decision maker can use the comparative information in reaching and justifying an objective decision. Additional information, such as the expected growth rate of a community or the effects of adding an additional water supply to any of the communities can also be readily calculated as necessary.

Local water supply managers and planners can use the drought severity and drought vulnerability indices calculated on a time basis (weekly, monthly) suited to their needs. The severity and vulnerability information defines when a drought begins or ends locally, how severe it is and what the probabilities are for drought in the immediate future. The calculation of the drought severity index (Equation 2) is not difficult and can be readily calculated and updated by anyone with a small amount of training. Computers and even small calculators are not necessary for the calculations.

The drought information can enhance the management of a local water supply. With the drought information a manager can determine:

1. When a drought begins or ends

2. What the probabilities are for drought conditions as they affect the water supply

3. When physical or voluntary adjustments to drought should be made

4. How restrictive to make adjustments to drought (price, restrictions, reuse, rotation, weather modification, emergency supplies)

5. Given population or increased use data, when to increase the existing water supply or when to seek funding for new supplies.

For example, in 1977 Monticello City determined to double their existing supply of water by drilling four wells. Had the problem been recognized in previous years and the drought severity information been available to substantiate the condition, perhaps the wells might have been drilled and the present severe drought conditions avoided. Orangeville City will construct a new water treatment plant during 1978. This is being done partly to alleviate drought conditions and partly to prepare for the influx of population related to energy development. The drought severity and vulnerability information can assist in determining the storage necessary and the size of the project, given population estimates, streamflow and water right data. This is done by adjusting the demand function to meet future needs and calculating the drought severity index with the available water as furnished demand.

The drought severity and vulnerability indices are important in overcoming the deficiencies in information about droughts, their severity and the probabilities of occurrence. It is expected that this information will assist water supply planners and managers in overcoming drought related problems.

Irrigation Area Results and Discussion

Background

To test the drought vulnerability and severity indices in an irrigational context, three irrigation areas with differing water supply characteristics are chosen. These include the Logan, Milford and Helper, Utah areas. The objective of this study is to calculate the drought indices for each irrigation area and evaluate by comparing the results with the Palmer Drought Index and public opinion as found in daily newspaper articles which relate to agricultural drought.

The irrigation demand (D_I) is calculated using the Blaney-Criddle method to obtain consumptive-use and then applying an irrigation efficiency coefficient that is consistant with irrigation practices in the area being studied. The monthly irrigation demand is summed for the irrigation season and included in the calculation of the seasonal drought severity index.

The furnished demand (F) parameter is taken in all cases as the amount of water historically diverted or pumped for irrigational uses. For the Helper and Milford irrigation areas, this amount is a seasonal total. In the Logan area case, both monthly and seasonal drought severity index values are calculated because data is available.

The drought vulnerability index is determined from the drought severity index values. The probability of water shortage, or vulnerability of an irrigation water supply system, is the probability that the drought severity index values will equal or exceed a certain critical value. Here, the critical value is chosen as the value where furnished demand (F) equals the irrigation demand (D_I), and the probability that $S \geq 0$ is calculated.

Historical diversion and pumpage records as well as the calculated drought severity index values are found in the Appendix. Graphical plots of the drought severity index values are included with the discussion of each irrigation area.

The Logan, Utah, irrigation area

The Logan area is located in the Northern mountains of Utah. Water is diverted from the Logan River to irrigate about 2400 acres served by the Logan, Hyde Park and Smithfield canal. Price of water is ignored because of the small charges involved. The drought severity index is calculated for the irrigation season April through September and for the individual months during the season. An irrigation efficiency of 50 percent (Haws, 1978) is also used in the calculation. These values are displayed in Figures 12 and 13. Because historically, very little water has been diverted during the month of April, it is determined that the month of April not be included in the calculation of the drought severity index. The justification for this assumption is that the low flows diverted to the canal were not resulting from drought conditions, but were the result of large winter carry-over water, the high frequency of spring (April) rains, the relatively high latitude and elevation of the study area and perhaps other factors also not being considered in this study. Values resulting from calculations of the drought severity index for the May-September irrigation season and the monthly drought severity values are found in Figures 14 and 15.

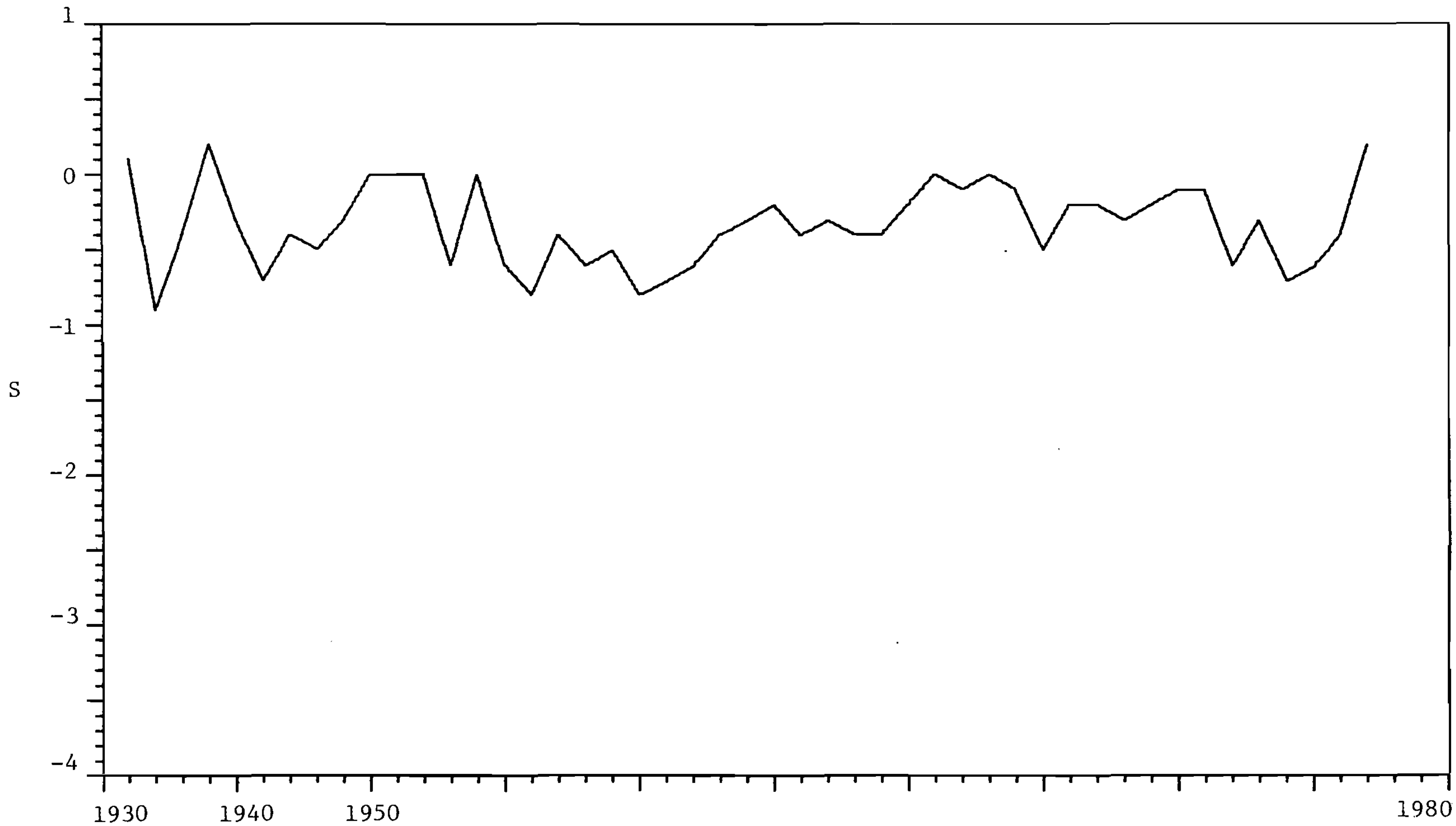


Figure 12. Logan, Hyde Park and Smithfield Canal irrigation area, drought severity index, seasonal (April-September) values.

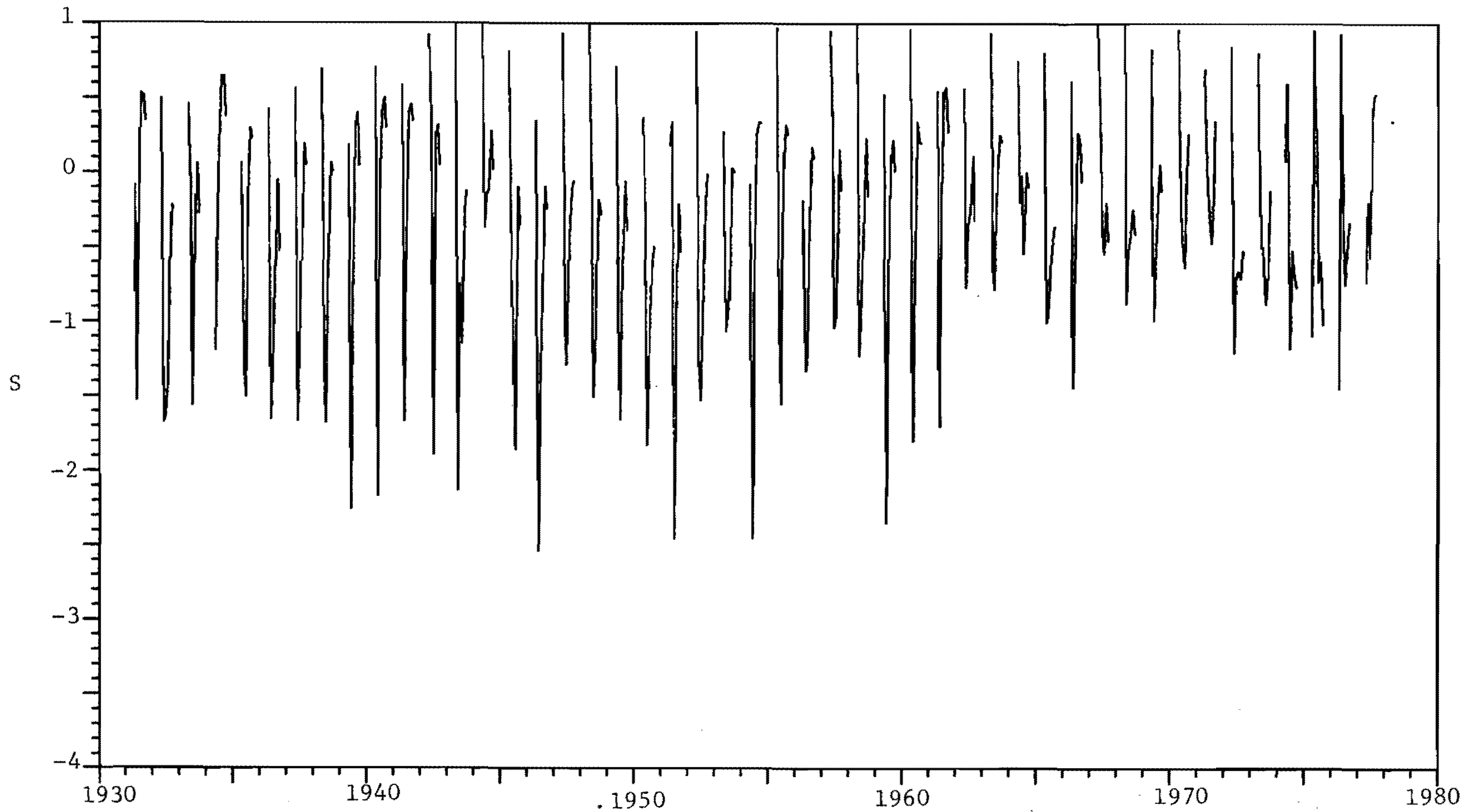


Figure 13. Logan, Hyde Park, and Smithfield Canal drought severity index, monthly valyes (April - September) for irrigation season.

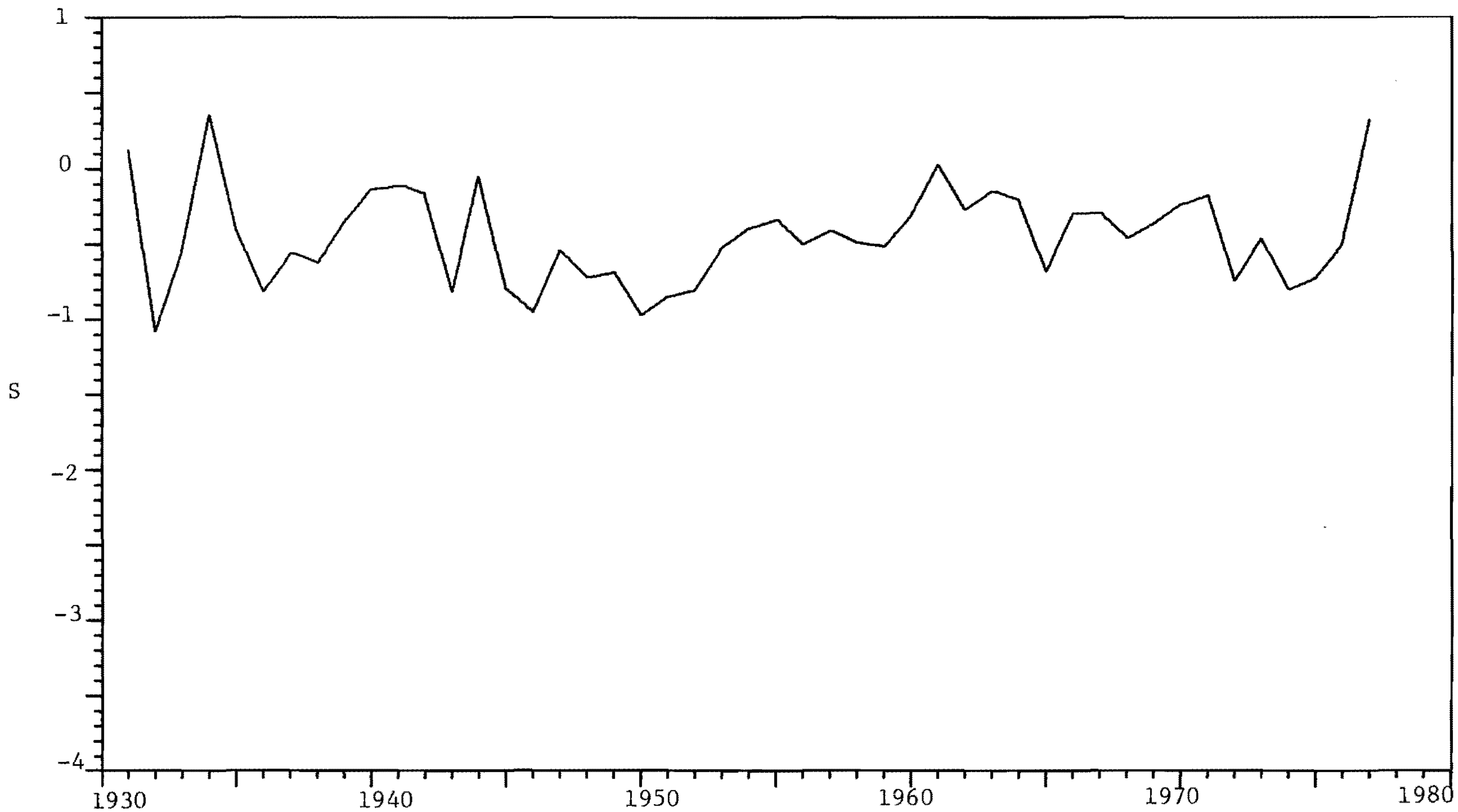


Figure 14. Logan, Hyde Park and Smithfield Canal drought severity index, seasonal (May - September) values.

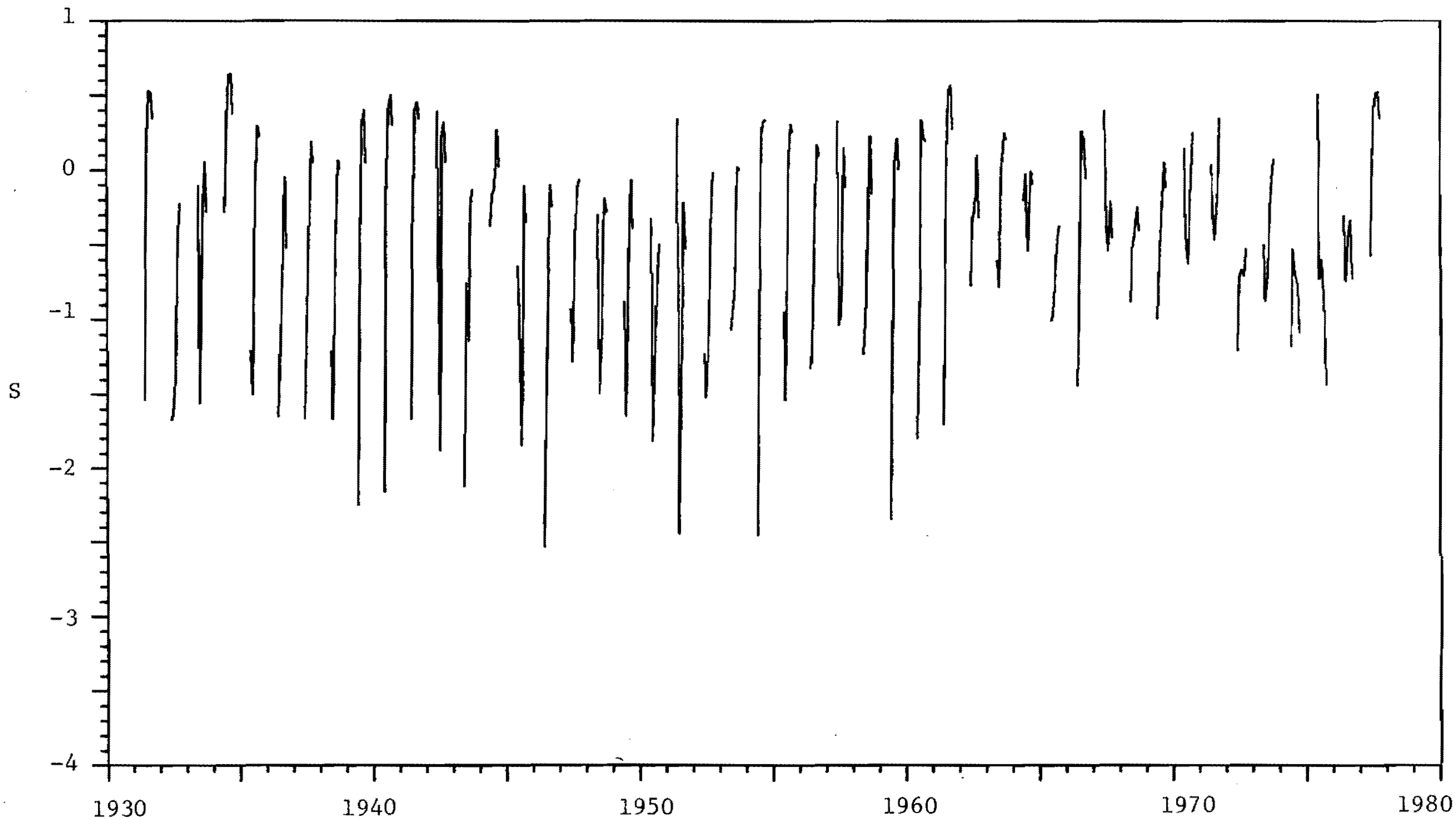


Figure 15. Logan, Hyde Park and Smithfield Canal drought severity index, monthly values (May-September) for irrigation season.

Table 25. Comparison of drought indices, for the Logan, Utah irrigation area (May-September)

Year	Seasonal Drought Severity Index Values	Moderate Palmer Drought Index Occurrences (Northern Mountains Region)	Number of Newspaper Articles (Agriculture)*
1931	.12	5	
1932	-1.08	4	
1933	- .53	5	
1934	.36	5	
1935	- .41	5	
1936	- .82	0	
1937	- .56	0	
1938	- .63	0	
1939	- .35	0	
1940	- .13	4	
1941	- .11	0	
1942	- .17	0	
1943	- .82	0	
1944	- .05	0	
1945	- .80	0	
1946	- .95	0	
1947	- .54	0	
1948	- .72	0	
1949	- .68	0	
1950	- .97	0	
1951	- .84	0	
1952	- .80	0	
1953	- .52	0	
1954	- .39	0	
1955	- .33	0	
1956	- .50	0	
1957	- .41	0	
1958	- .49	2	2
1959	- .52	0	10
1960	- .31	4	8
1961	.03	3	9
1962	- .27	0	1
1963	- .15	2	5
1964	- .21	0	4
1965	- .68	0	0

Table 25. Continued.

Year	Seasonal Drought Severity Index Values	Moderate Palmer Drought Index Occurrences (Northern Mountains Region)	Number of Newspaper Articles (Agriculture)*
1966	- .29	0	7
1967	- .29	0	0
1968	- .46	0	0
1969	- .36	0	2
1970	- .23	0	0
1971	- .17	0	1
1972	- .74	0	12
1973	- .46	0	0
1974	- .80	2	14
1975	- .72	0	0
1976	- .50	0	1
1977	.33	5	

*Not available 1931-1957, 1977

The drought vulnerability, or probability of water shortage in the immediate future is calculated as 8.56 percent for the irrigation season and 22.2 percent for the monthly irrigation season. This means that there is only about a 9 percent chance that the coming irrigation season will have a water shortage condition severe enough to affect the total season. The vulnerability of 22 percent for the monthly values means that there is a 22 percent chance that any month in the season will have a water shortage.

For comparison purposes, the drought severity index is tabulated with the moderate Palmer Drought Index and public opinion values from a daily newspaper. These values are found in Table 25. Four years, 1931, 134, 1961 and 1977 are recorded as drought years using the drought severity index. All of these years are also reporting drought using the Palmer Drought index. The years of 1932, 1933, 1935, 1940 and 1960 are also droughts according to the Palmer Index. There is no correspondence with the drought severity index for the years 1932, 1933 and 1935 and it is assumed that the meteorologic drought persistance during the early 1930's is responsible. The years of 1940 and 1960 do relate the two indices, for during each of these years the drought severity index becomes less negative. There appears to be no correspondence between the indices mentioned above and the occurrence of newspaper articles on agricultural drought during the 1958-1976 period.

From the results and comparisons above, it can be stated that the drought severity index provides at least as much information about the effects of drought on a water supply system as does the regional, more difficult Palmer Drought Index. The drought severity index also provides a frame of reference for defining the effects of an agricultural drought.

The Milford, Utah irrigation area

The Milford irrigation area is located in the valley south of Milford, Utah. The irrigation area studied received all of its water from groundwater pumping. Price of water is not included because the horsepower ratings of the several irrigation pumps is unknown. The months April through September is used as the irrigation season and the drought severity index values are calculated for each season using total well pumps as furnished demand (F) and the irrigation demand (D_I) as calculated in the Blaney-Criddle method. A farm efficiency of 60 percent is applied because (Griffin, 1978) the area uses sprinkler irrigation almost exclusively.

The drought severity index values calculated for the area are included in Table 26. A plot of the values is found in Figure 16.

The drought vulnerability index is calculated as 97.7 percent. This means that there is 97.7 percent chance each season of incurring water shortage. Three reasons could be responsible for the high percentage. The first is that the price of pumping water is quite high and the farmers are willing to accept some water shortage rather than incur the high cost of pumping. A second reason is that perhaps the irrigation efficiency is higher than described by Griffin (1978). The third reason is that the drought severity index may be incorrect. The author is convinced, however, that the first reason (high cost of pumping is responsible and that further studies on prices and horsepower ratings in the area will disclose the problem. It is

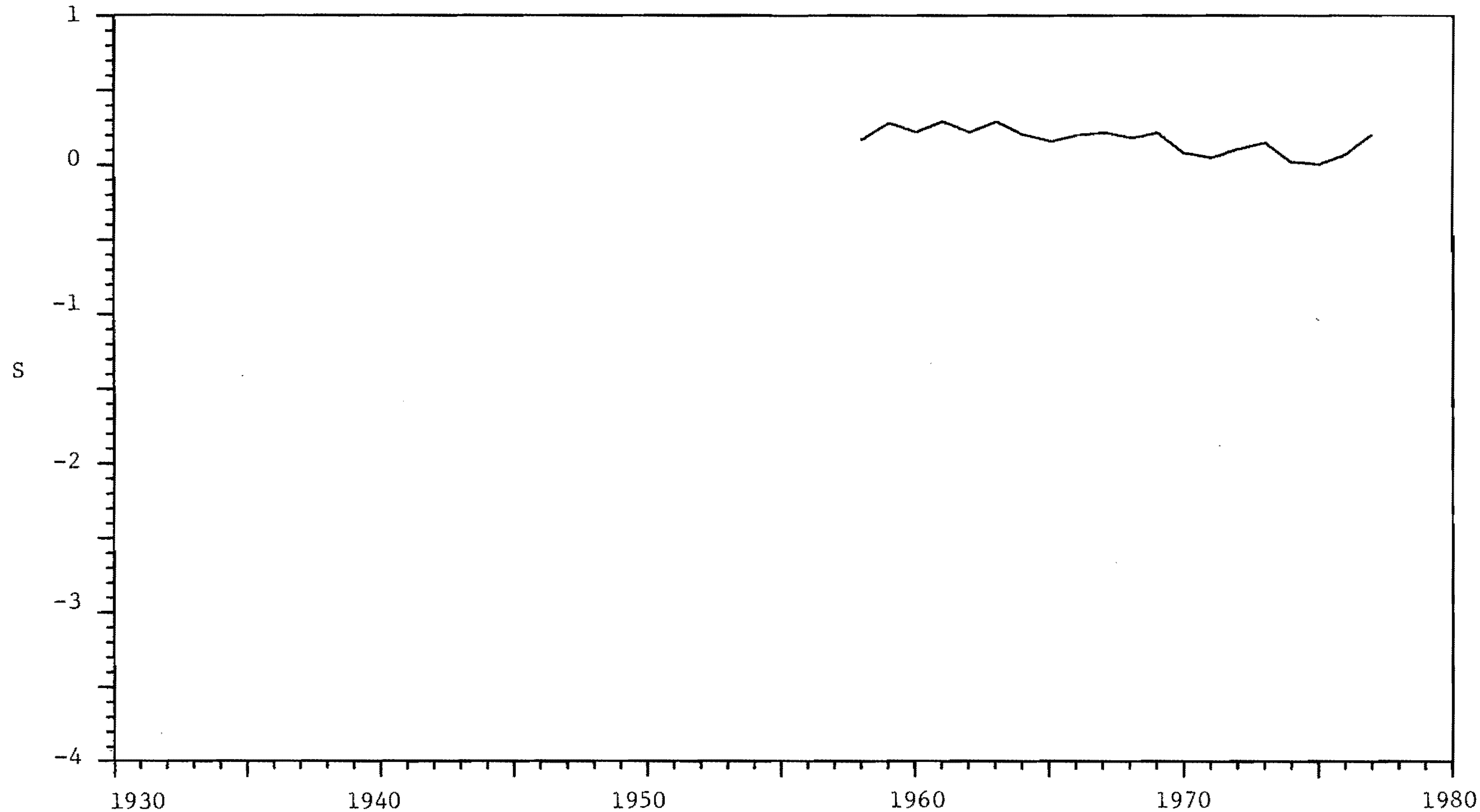


Figure 16. Milford irrigation area drought severity index, seasonal values.

important that the drought severity index as formulated be retained in a consistant manner as a control.

For comparative purposes the drought severity index values are found with the moderate Palmer Drought Index and the number of newspaper articles in Table 26. The period 1959 through 1963 and the year 1977 all appear to be drought conditions in the Milford area as shown by the indices. For other years, however, there appears to be no correlation among the indices.

The Helper, Utah irrigation area

The Oberto Ditch is a small canal to which waters from the Price River are diverted to irrigate about 66 acres of land. The period of record extends from 1942 through 1976. Data for the drought of 1977 was not available because a flash flood early in the irrigation season destroyed the diversion control device. As with the other irrigation areas, price of water is not included in the calculation of the drought severity index. The irrigation season is defined as the months April through September and the seasonal drought severity index is calculated using the total amount of water diverted as furnished demand (F). Irrigation demand (D_I) is determined using the Blaney-Criddle method for computing consumptive-use. An irrigation efficiency coefficient of 40 percent (Griffin, 1978) is applied. Drought severity index values are shown in Figure 17. The drought vulnerability index as calculated for the area is 44.5 percent, which means that the area served by the canal can expect water shortages about 45 percent of the time.

Table 27 contains the drought severity index values, the moderate Palmer Drought Index occurrences and the number of newspaper articles

Table 26. Comparison of drought indices for the Milford, Utah irrigation area.

Year	Seasonal Drought Severity Index Values	Moderate Palmer Drought Index occurrences	Number of Newspaper Articles (Agriculture)
1958	.17	0	2
1959	.28	6	10
1960	.22	6	8
1961	.29	4	9
1962	.22	0	1
1963	.29	5	5
1964	.20	0	4
1965	.16	0	0
1966	.20	0	7
1967	.22	0	0
1968	.18	0	0
1969	.22	0	2
1970	.08	0	0
1971	.05	0	1
1972	.11	4	12
1973	.15	0	0
1974	.02	4	14
1975	.00	0	0
1976	.07	0	1
1977	.20	5*	**

*Only April-August considered

**Not available

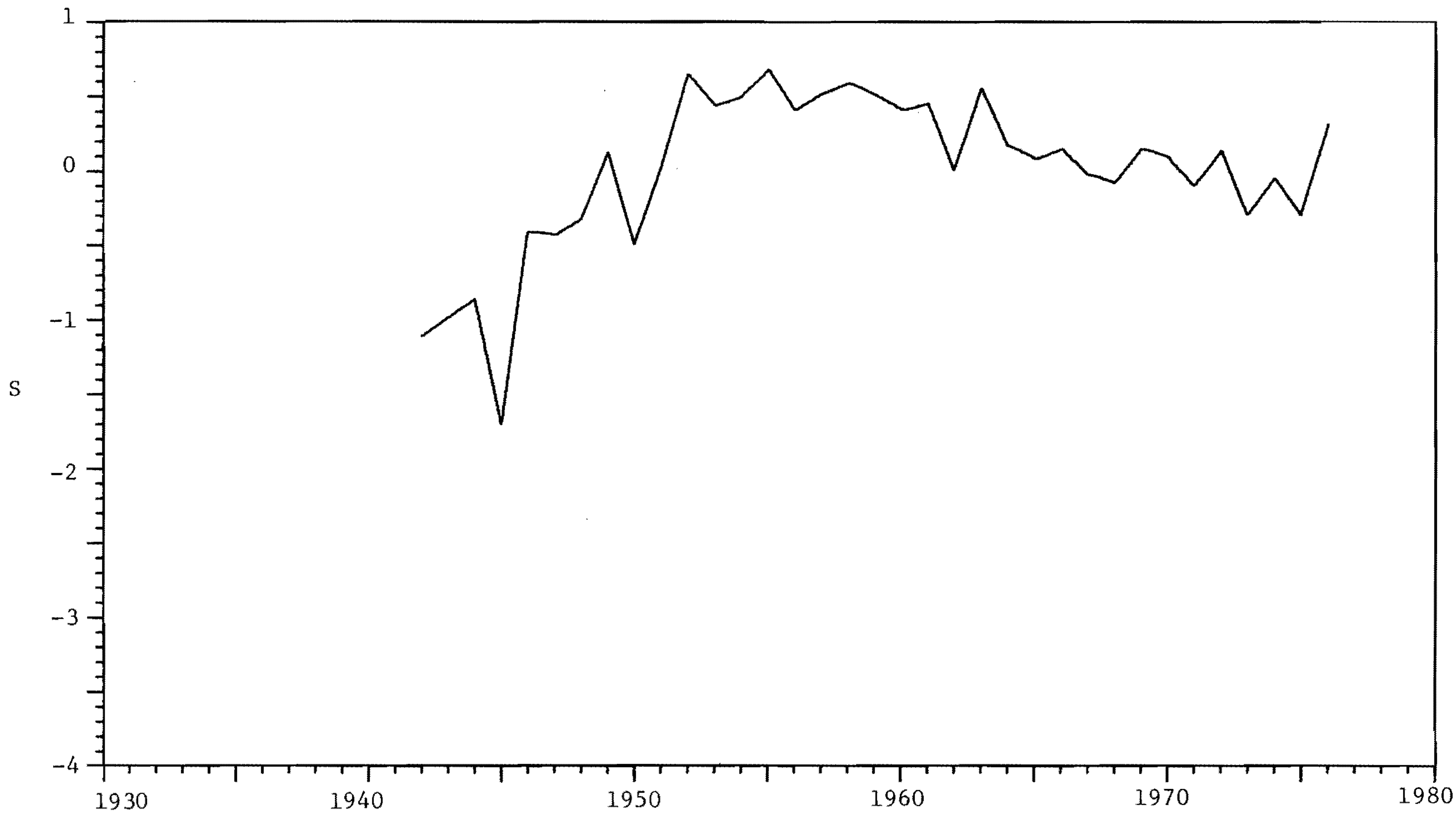


Figure 17. Oberto Ditch (Helper, Utah) irrigation area, drought severity index, seasonal values.

Table 27. Comparison of drought indices for the Helper, Utah (Oberto Ditch) irrigation area.

Year	Seasonal Drought Severity Index Values	Moderate Palmer Drought Index Occurrences (Southeastern Region)	Number of Newspaper Articles*
1942	-1.11	0	
1943	-0.98	4	
1944	-0.86	0	
1945	-1.70	0	
1946	-0.41	5	
1947	- .43	3	
1948	- .32	0	
1949	.13	0	
1950	- .49	5	
1951	.03	4	
1952	.65	0	
1953	.44	1	
1954	.50	5	
1955	.68	2	
1956	.41	6	
1957	.52	0	
1958	.59	0	2
1959	.51	6	10
1960	.41	6	8
1961	.46	4	9
1962	.01	0	1
1963	.56	5	5
1964	.17	0	4
1965	.08	0	0
1966	.15	0	7
1967	- .02	0	0
1968	- .08	0	0
1969	.15	0	2
1970	.09		
1971	- .10	0	1
1972	.14	4	12
1973	- .29	0	0
1974	- .04	4	14
1975	- .29	0	0
1976	.32	0	1

*Data not available 1942-1957

dealing with agricultural drought in the daily, regional newspaper. About half of the Palmer Drought Index Values appear to compare favorably with the drought severity index, but the magnitude of the values vary greatly.

Comparing results of the irrigation areas

Even thought it is realized that the Palmer Drought Index is measuring meteorological drought on a regional scale, it is expected that the drought severity index will compare favorably with it on a general basis. The results show that little if any correspondence exists between the indices.

The drought severity indices for the three irrigational areas for the period 1958 through 1977 are found in Table 28. A cross-sectional comparison of the data, especially during years of known drought (1961, 1963, and 1977) lead to the conclusion that each area is effected by drought, but the Milford area is effected much more severely than are the other two areas. It should be noted that the 1977 drought conditions affected the Logan Area (dependent upon natural streamflow) more severely than the Milford Area (dependent upon groundwater pumpage). For these reasons the drought severity and vulnerability data are accepted as being indices of drought conditions with the assumption that as price of water is included and by using time periods of weekly or monthly durations, the indices will be further refined.

The use of the drought severity index for planning purposes

The drought severity index can be used to gain information about past, current, or future drought conditions. Having discussed past

Table 28. Drought severity index comparison among the irrigation areas.

	Drought Severity Index Values		
Year	Logan Area	Milford Area	Helper Area
1958	-.49	.17	.59
1959	-.52	.28	.51
1960	-.31	.22	.41
1961	.03	.29	.46
1962	-.27	.22	.01
1963	-.15	.29	.56
1964	-.21	.20	.17
1965	-.68	.16	.08
1966	-.29	.20	.15
1967	-.29	.22	-.02
1968	-.46	.18	-.08
1969	-.36	.22	.15
1970	-.23	.08	.09
1971	-.17	.05	-.10
1972	-.74	.11	.14
1973	-.46	.15	-.29
1974	-.80	.02	-.04
1975	-.72	.00	-.29
1976	-.50	.07	.32
1977	.33	.20	*

*1977 data not available

and current applications, the objective of this section is to show how future drought information might be obtained. In order to accomplish this objective, the Logan irrigation area is chosen as a study case. The generation of drought information is accomplished in five steps.

1. Generate synthetic water supply data,

2. Generate synthetic mean temperatures to be used in the calculation of the demand function.

3. Using the drought model for the Logan irrigation area, generate synthetic drought severity index values.

4. Calculate the drought vulnerability index.

5. Evaluate results.

The first step is accomplished in two phases. The Logan study area receives its irrigation water from the Logan, Hyde Park and Smithfield canal. The canal diverts water from the Logan River. Therefore, monthly synthetic streamflow for the Logan River is generated and then monthly synthetic canal diversions are derived from the Logan River streamflow.

The synthetic streamflow for the Logan River are generated using the univariate ARIMA model described in detail in Chapter III. Of the 220 years of record generated, the first 20 years are not used to remove any bias resulting from boundary conditions. The synthetic data for the 200 years (2400 data points) retain their specific month identity. Now, using only those months representing the irrigation season, the Logan, Hyde Park, and Smithfield Canal diversions are calculated.

Canal diversions are derived from the synthetic Logan River streamflow values according to the legal constraints of the Kimball Decree (see Figure 6 and Haws, 1965). Because these values were rather high as compared to historical diversions (Table 13), the expected value of the historical percentage for the 1961-1977 period is also calculated (see Table 14). The synthetic canal diversions as calculated are used in the planning model as furnished demand (F).

In order to calculate the irrigation demand function the mean monthly temperature is necessary. To provide an estimate for these values, a normal, independent random number is generated. This random number is multiplied by the standard deviation for each month and that month's expected value is added to obtain an estimate of the mean temperature for the month (see Chapter III). With the mean temperature estimate, the irrigation demand function and the drought severity index can be calculated. The results of the drought severity index are included in the Appendix. For the monthly data the drought vulnerability index is 4.9 percent. For the seasonal synthetic data the drought vulnerability index is 0.0003 percent. These values mean that less than 1 percent of the time are drought conditions expected to occur on a seasonal basis. For the monthly data, 108 months in the 2400 month period are expected as water shortage months. These limits appear low, but using the high legal limits and physical constraints, the value is expected to be low. The method and application are the essential ingredients here. It is important to note that:

1. A time series model can be constructed to generate synthetic values of water supply.

2. The demand function for a municipality or an irrigation area can be calculated given future population estimates or the legal constraints of the system.

3. Drought severity and vulnerability index values can be created from the synthetic data which will greatly increase the information about future droughts and water supply adequacy.

Application of the Model

From the above descriptions of the drought severity and vulnerability indices, it is seen that the model works very well for the municipalities and fair for the irrigation areas. To apply the model one needs only to gather the necessary water supply data, temperature data and population estimates. From these values, the indices can be calculated.

Once the drought severity and vulnerability indices are calculated much information is available. For example: the adequacy of the water supply system is evident; the present status of the system is easily determine when compared with the recent past severity values; occurrence of drought is easily obtained; the empirical probability values for the run sum, run length and peak are available; the beginning and ending of drought periods can be determined with accuracy; the critical level of drought severity may be changed and refined according to area suitability; comparisons can be made among other affected areas; the calculations are simple enough to be refined and updated on a regular basis; and planners and managers have objective data with which to make decisions and justify them.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The objective of this study was to develop a relatively simple and practical method for improving the availability and reliability of information about droughts to those responsible for water supply management and planning. The information technique developed provides an objective basis for the selection of water supply management alternatives during periods of drought. The derived drought information can assist water supply planners and managers in identifying priorities among proposed water supply developments from consideration of water supply vulnerability and existing drought severity levels.

Two drought indices are developed to achieve the overall objective of the study: (1) the drought severity index for describing the state of drought as it affects a water supply system and (2) the drought vulnerability index which indicates the probability of water shortage in a water supply system. In addition, the autoregressive integrated moving average (ARIMA) method is used to develop a model representative of a water supply system and from the model synthetic data are generated using Monte Carlo methods. The synthetic data are utilized in the drought severity and vulnerability indices and the probabilities of future water shortage are calculated.

In this study the drought severity and vulnerability indices are conceptualized and tested for water supplies of three communities and three irrigation areas. Comparisons are made among the test cases. Excellent results are obtained from the municipality group and fair results are derived from the irrigation areas. Definitions of drought severity, vulnerability, drought beginning and ending are derived. These can be applied to local water supply systems. The definitions and indices are more applicable, more simplified and are more responsive to local water supply systems than are the alternative definitions which are available in literature. In the absence of good, objective drought information for comparing alternatives the drought severity and vulnerability indices provide easily calculated objective drought information. These techniques are excellent for regional comparison uses, planning or for managing a water supply system on a local basis. For example, the City of Monticello, Utah determined during the past year to drill four wells which will double the existing water supply. The drought vulnerability information calculated in this study (though not available for the Monticello City planners), noted that the probability of water shortage in the immediate future is 46 percent when water is priced at $0.20 per thousand gallons. Were the price raised to $2.00 per thousand gallons the probability is 17 percent. Assuming that a certain level of water shortage is unacceptable, say 15 percent, it is obvious that the City of Monticello should not try to "price" themselves out of drought conditions but to increase their water supply in an increment at least large enough to decrease the probability of water shortage to an acceptable level at an acceptable price.

Another case is the City of Orangeville, Utah. The managers of that city have determined to increase the size of their culinary water treatment plant to decrease drought conditions. The drought vulnerability for Orangeville at $0.20 per thousand gallons is 35%. Were the price raised to $2.00 per thousand gallons, the probability of water shortage decreases to 6 percent. In this case perhaps a viable alternative would be to increase water prices to at least $1.00 per thousand gallons (probability of water shortage is 11 percent). The conclusion is that the increased drought information presents objective information and increases the range of alternatives for water supply planners and managers.

Recommendations for Further Study

1. Price is an important factor in defining the demand function for water supplies. Price should be included in the demand function for irrigation areas. For groundwater pumping areas, this can be accomplished using pump horsepower ratings and electricity rate schedules.

2. The demand function for the municipalities used in this study is an annual demand function, weighted by monthly coefficients. Data should be collected and the real monthly demand values derived. This should give better resolution to the drought indices.

3. Drought consequence data should be collected in areas studied to evaluate the results of drought severity model calculations. The Palmer Drought Index and public opinion as measured by counting newspaper articles are not adequate.

4. A study should be conducted where synthetic water supply

data is generated for a municipality. The Box-Jenkins ARIMA methodology is recommended. With these values, the effect of increased or decreased population on a water supply system can be tested. This would be especially appropriate in the energy developmental areas of Utah.

5. A loss function should be established from economic considerations (see Russel, et al., 1970) so that the drought severity and probability might be evaluated in terms commensurate with water supply augmentation alternatives. Perhaps a crop yield model might be used to evaluate the loss function for an irrigation area.

6. A better method of testing irrigation areas for drought is recommended. During a drought, farmers realize there are drought conditions and make adjustments for it by planting alternate crops, managing water better, etc. Suggested is checking at local banks and mortgage companies to find how many farmers go out of business during drought as opposed to those going out of business during "wet" years.

7. Several similar and more complex water supply systems should be studied and compared. The results of this study are logical, but there is no absolute conclusion. More data is needed in this area.

8. A method should be determined to generate "real" canal diversions instead of relying upon legal water right constraints. This step would base the drought indices on reality instead of legal terms and the resulting probabilities would be representative of the irrigation area and not of the legal implications of the canal capacity.

9. Drought forecasting and planning for drought in water supply systems should be considered in light of the drought severity and drought vulnerability indices. The drought forecasting can probably be done by forecasting the water supply (streamflow) and combining that forecast with population or temperature prognostications. These values could then be incorporated into the drought severity index.

10. Much drought data needs to be collected so that the frequency distributions of run lengths and sum of the positive deviations of the drought severity index might be calculated. This will undoubtedly provide more information about drought conditions and quite possibly could be used as another indicator of water supply adequacy.

11. An educational method should be established to educate the water supply planners and managers on the methods of evaluating drought using the techniques developed in this study. Information of any kind is of no value unless it is available to those who can use it.

12. The drought severity indices, Palmer Drought Index and the number of newspaper articles data were regressed using the accumulative totaling technique and the correlations were found to be significant. Data as to the effect of drought on specific water supply systems, rather than regional data, should be collected to further test the adequacy of the drought severity index as developed here.

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APPENDICES

Appendix A

Evapotranspiration Calculations

Evapotranspiration Model Comparisons

Crop = Alfalfa   Acres = 160   Farm Efficiency = 60 %

1. Blaney-Criddle Method

Month	t	p	k_t	k_c	$\frac{k_c k_t t p}{100}$
May	52.0	10.13	0.586	1.08	3.33
Jun	67.6	10.24	0.855	1.13	6.69
Jul	70.3	10.35	0.902	1.11	7.29
Aug	67.7	9.62	0.857	1.06	5.92
Sep	59.6	8.40	0.717	0.99	3.55
				Net Sum	26.78"
				Gross Sum	44.63" or 595 AF

2. Other Methods

Month	k_{co}	Hargreaves E_{tp}	Hargreaves E_t	Jensen - Haise E_{tp}	Jensen - Haise E_t
May	0.61	4.24	2.59	4.15	2.53
Jun	0.85	7.26	6.17	7.86	6.68
Jul	0.92	7.19	6.61	7.87	7.24
Aug	0.92	5.89	5.42	6.39	5.87
Sep	0.81	4.28	3.47	4.47	3.62
		Net Sum	24.26"		25.94"
		Gross Sum	40.4" or 539 AF		43.2" or 576 AF

Month	Penman E_{tp}	Penman E_t	Pan Evaporation
May	4.55	2.78	4.43
Jun	7.61	6.47	8.81
Jul	7.62	7.01	7.31
Aug	6.66	6.13	6.37
Sep	5.40	4.37	3.61
Net Sum		26.76"	30.53"
Gross Sum		43.2" or 595 AF	50.88" or 678 AF

Appendix B

Data and Drought Severity Index (S) Calculations

Milford City

DROUGHT SEVERITY INDEX VALUES — WATER DEMAND PRICE IS $0.20 PER THOUSAND GALLONS

YEAR	[illegible]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
[illegible]	[illegible]	1.00	[illegible]	1.00	1.00	1.00	1.00	1.00	-0.49	-0.11	-0.06	-0.32	-0.01
[illegible]	[illegible]	[illegible]	-1.15	-0.51	0.62	-0.20	-0.05	-0.30	-0.05	-0.50	-0.01	-0.17	-0.30
[illegible]	[illegible]	[illegible]	[illegible]	-0.29	-0.60	-0.59	-0.61	-0.34	-0.43	-0.59	0.18	0.03	-0.15
[illegible]	[illegible]	[illegible]	-1.20	-0.22	-0.38	-0.57	-1.18	-0.41	-0.23	-0.48	0.04	-0.22	0.05
1971	1515	-0.29	-0.06	-0.11	-0.50	-0.14	-0.45	-0.55	-0.33	0.20	-0.93	-0.10	-0.27
[illegible]	[illegible]	-0.18	-0.71	-1.20	-0.35	-0.54	-0.43	-0.65	-0.26	-0.30	0.19	-1.00	-1.04
[illegible]	[illegible]	[illegible]	-0.51	-0.35	0.04	0.23	-0.41	-0.59	-0.51	0.24	-1.03	-0.30	-0.33
[illegible]	[illegible]	-0.16	[illegible]	-0.16	-0.59	-0.25	-0.64	-0.61	-0.62	-0.21	-0.45	-0.20	-0.32
[illegible]	[illegible]	-0.39	-0.54	-0.16	-0.09	0.01	-0.33	-0.51	-0.42	-0.48	-0.35	-0.33	-0.25
[illegible]	[illegible]	-0.52	[illegible]	-0.27	-0.25	-0.64	-0.59	-0.45	-0.16	-0.82	-1.16	-0.75	-0.42
1977	[illegible]	[illegible]	[illegible]	-0.27	-1.42	1.05	0.04	1.00	1.00	1.00	1.00	1.00	1.00

DROUGHT SEVERITY INDEX VALUES — WATER DEMAND PRICE IS $0.50 PER THOUSAND GALLONS

YEAR	[illegible]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
[illegible]	[illegible]	[illegible]	[illegible]	1.00	1.00	1.00	1.00	1.00	-0.64	-0.22	-0.17	-0.45	-0.12
[illegible]	[illegible]	[illegible]	-0.20	[illegible]	-0.08	-0.52	-0.60	-0.52	-0.16	-0.72	-0.11	-0.29	-0.44
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.10	-0.75	-0.11	-0.48	-0.57	-0.75	0.10	-0.07	-0.10
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.28	-0.75	-0.50	-0.55	-0.55	-0.63	-0.06	-0.35	-0.04
[illegible]	[illegible]	[illegible]	-1.17	-0.22	-0.65	-0.26	-0.59	-0.71	-0.47	0.12	-1.12	-0.21	-0.39
[illegible]	[illegible]	[illegible]	[illegible]	-1.51	-0.52	-0.69	-0.57	-0.82	-0.41	-0.43	0.10	-1.20	-1.25
[illegible]	[illegible]	[illegible]	-0.47	-0.46	-0.05	0.16	-0.55	-0.75	-0.66	0.17	-1.25	-0.45	-0.47
[illegible]	[illegible]	-0.28	[illegible]	-1.27	-0.75	-1.04	-0.60	-0.70	-0.78	-0.33	-0.59	-0.32	-0.43
[illegible]	[illegible]	-1.55	-0.71	[illegible]	-0.20	-0.09	[illegible]	-0.90	-0.51	-1.10	-0.40	-0.40	-0.39
[illegible]	[illegible]	[illegible]	-0.45	-0.40	-0.30	-1.05	[illegible]	-0.80	-0.28	-1.09	-1.40	-0.95	-1.11
1977	[illegible]	[illegible]	-0.41	-0.40	-1.60	-0.04	-0.06	1.00	1.00	1.00	1.00	1.00	1.00

DROUGHT SEVERITY INDEX VALUES — WATER DEMAND PRICE IS $1.00 PER THOUSAND GALLONS

YEAR	[illegible]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
[illegible]	1271	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-0.77	-0.34	-0.25	-1.57	-0.21
[illegible]	[illegible]	[illegible]	-1.57	-0.38	-0.17	-0.45	-0.75	-0.65	-0.35	-0.78	-0.21	-0.39	-0.02
[illegible]	[illegible]	[illegible]	-0.35	-0.50	-0.20	[illegible]	-0.20	-0.60	-0.70	-0.29	0.05	-0.10	-0.26
[illegible]	[illegible]	[illegible]	-0.54	-0.45	-0.64	-0.89	[illegible]	-0.68	-0.47	-0.76	-0.14	-0.46	-0.13
[illegible]	[illegible]	-0.54	-0.20	-0.52	-0.79	-0.56	-0.73	-0.55	-0.54	0.05	-1.36	-0.31	-0.51
[illegible]	[illegible]	[illegible]	[illegible]	-1.71	-0.65	-0.65	-0.70	-0.97	-0.52	-0.55	0.03	-1.38	-1.43
[illegible]	[illegible]	[illegible]	[illegible]	-0.50	-0.14	0.09	-0.68	-1.90	-0.80	0.10	-1.42	-0.55	-0.59
[illegible]	[illegible]	-0.39	-0.77	-0.30	-0.89	-1.20	-0.95	-1.12	-0.94	-0.44	-0.75	-0.43	-0.55
[illegible]	[illegible]	-0.56	-0.54	-0.39	-0.30	-0.16	-0.55	-0.80	-0.04	-1.36	-0.58	-0.58	-0.51
[illegible]	[illegible]	-0.57	-0.35	-0.51	-0.64	-1.19	-0.69	-0.75	-0.59	-1.17	-1.59	-1.08	[illegible]
1977	[illegible]	-2.37	-0.53	-0.51	-1.06	-0.13	-0.15	1.00	1.00	1.00	1.00	1.00	1.00

DROUGHT SEVERITY INDEX VALUES — WATER DEMAND PRICE IS $2.00 PER THOUSAND GALLONS

YEAR	[illegible]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1967	[illegible]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-0.93	-0.44	-0.30	-0.71	-0.31
[illegible]	[illegible]	-0.35	[illegible]	-1.70	-0.26	-0.55	-0.85	-0.75	-0.37	-1.03	-0.31	-0.52	-0.76
[illegible]	[illegible]	[illegible]	-1.05	[illegible]	-0.50	[illegible]	-0.31	-0.74	-0.45	-1.10	-0.06	-0.26	-0.37
[illegible]	[illegible]	-0.51	[illegible]	-0.36	-0.79	-1.06	-0.54	-0.83	-0.50	-0.92	-1.25	-0.59	-0.25
1971	1515	[illegible]	-0.37	-0.44	-0.95	-1.06	-0.66	-1.01	-0.75	-0.04	-1.50	-0.42	-0.04
1972	[illegible]	-0.53	-1.22	-1.95	-0.79	-1.00	-0.67	-1.14	-0.66	-0.69	-0.06	-1.59	-1.65
1973	[illegible]	[illegible]	-1.90	-0.72	-0.24	0.01	-0.85	-1.07	-0.96	0.92	-1.03	-0.69	-0.73
[illegible]	[illegible]	-0.51	-0.45	-0.50	-1.00	-1.40	-1.12	-1.07	-1.10	-0.57	-0.88	-0.56	-0.69
[illegible]	[illegible]	-0.31	-1.08	-0.51	-0.41	-0.29	-0.72	-0.96	-0.70	-1.57	-0.72	-0.72	-0.84
[illegible]	[illegible]	-0.71	-0.69	-0.65	-0.62	-1.39	-1.06	-0.86	-0.51	-1.36	-1.82	-1.27	-1.49
1977	[illegible]	-2.67	-2.00	-0.65	-2.13	-0.23	-0.25	1.00	1.00	1.00	1.00	1.00	1.00

Monticello City

DROUGHT SEVERITY INDEX VALUES — WATER DEMAND PRICE IS $0.20 PER THOUSAND GALLONS

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1966	[illegible]	-0.27	-0.27	-0.19	-0.23	-0.12	-0.04	0.15	0.07	0.18	0.18	-0.00	0.53
1967	[illegible]	[illegible]	0.02	0.13	0.17	-0.10	0.23	0.19	0.10	-0.01	0.04	0.24	0.55
1968	1512	0.27	0.24	0.35	0.35	-0.08	0.00	-0.04	0.22	-0.37	-0.57	-0.40	0.07
1969	1471	0.25	0.19	0.34	-0.15	-0.40	-0.05	-0.31	-0.38	-0.57	-0.58	0.05	-0.11
1970	1431	-0.12	-0.25	-0.15	0.21	-0.06	-0.23	-0.39	-0.12	-0.07	-0.15	-0.27	-0.15
1971	15..	0.41	-0.15	-0.11	-0.46	-0.03	-0.15	-0.14	-0.00	-0.10	0.11	-0.05	-0.10
1972	1575	-0.21	-0.22	-0.54	-0.25	-0.36	-0.07	-0.11	-0.12	0.15	0.05	-0.34	-0.11
1973	[illegible]	[illegible]	[illegible]	0.05	0.26	0.20	0.03	-0.25	-0.33	-0.34	-0.40	-0.58	-0.37
1974	[illegible]	[illegible]	[illegible]	-0.16	-0.15	-0.35	-0.23	0.14	0.25	0.40	0.16	0.04	-0.10
1975	[illegible]	[illegible]	0.10	0.13	0.53	0.34	-0.13	0.11	-0.09	-0.22	-0.03	-0.15	-0.20
1976	1750	-0.21	-0.14	0.00	0.01	0.10	-0.05	-0.09	-0.14	-0.02	0.15	0.05	-0.01
1977	1774	0.13	0.43	0.50	0.49	0.78	0.81	0.72	0.63	1.00	1.00	1.00	1.00

DROUGHT SEVERITY INDEX VALUES — WATER DEMAND PRICE IS $0.50 PER THOUSAND GALLONS

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1966	[illegible]	[illegible]	[illegible]	-0.31	-0.56	-0.23	-0.15	0.07	-0.02	0.09	0.09	-0.10	-0.07
1967	[illegible]	[illegible]	[illegible]	0.05	[illegible]	-0.21	0.15	0.11	0.01	-0.11	-0.06	0.16	0.26
1968	[illegible]	[illegible]	[illegible]	0.28	0.26	-0.19	-0.10	-0.14	0.14	-0.51	-0.73	-0.54	[illegible]
1969	[illegible]	[illegible]	0.11	0.27	-0.26	-0.54	-0.16	-0.44	-0.52	-0.72	-0.74	-0.05	-0.22
1970	[illegible]	-0.23	-0.38	-0.25	0.14	-0.17	-0.35	-0.53	-0.23	-0.17	-0.26	-0.40	-0.27
1971	[illegible]	[illegible]	-0.30	-0.22	-0.61	-0.13	-0.27	-0.30	-0.11	-0.21	0.02	-0.15	-0.21
1972	1575	-0.11	-0.12	-0.70	-1.03	-0.49	-0.17	-0.22	-0.23	0.07	-0.07	-0.14	-0.22
1973	[illegible]	-0.07	-0.10	-0.05	0.21	0.12	-0.07	-0.57	-0.47	-0.48	-0.54	-0.65	-0.51
1974	[illegible]	[illegible]	-0.19	[illegible]	-0.27	-0.66	-0.35	0.05	0.18	0.34	0.07	[illegible]	[illegible]
1975	[illegible]	[illegible]	0.01	0.45	0.26	0.27	-0.24	0.02	-0.20	-0.34	-0.13	-0.27	-0.35
1976	[illegible]	[illegible]	-0.25	-0.10	-0.06	0.01	-0.19	-0.20	-0.25	-0.13	0.06	-0.05	-0.11
1977	1774	[illegible]	0.37	0.28	0.44	0.76	0.79	0.70	0.60	1.00	1.00	1.00	1.00

DROUGHT SEVERITY INDEX VALUES — WATER DEMAND PRICE IS $1.00 PER THOUSAND GALLONS

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1966	1576	-0.51	-0.51	-0.42	-0.47	-0.33	-0.24	-0.01	-0.11	0.02	0.02	-0.14	-0.15
1967	15..	-0.12	-0.17	-0.03	0.01	-0.31	0.08	0.03	-0.07	-0.20	-0.15	0.09	0.20
1968	1512	0.13	0.14	0.22	0.20	-0.29	-0.19	-0.24	0.07	-0.64	-0.87	-0.67	-0.11
1969	1471	0.11	0.44	0.21	-0.37	-0.66	-0.25	-0.50	-0.64	-0.87	-0.88	-0.14	-0.32
1970	1431	-0.34	-0.49	-0.35	0.07	-0.26	-0.47	-0.65	-0.33	-0.27	-0.37	-0.52	-0.37
1971	15..	-0.17	-0.41	-0.42	-0.74	-0.23	-0.57	-0.41	-0.20	-0.31	-0.06	-0.25	-0.31
1972	1575	-0.24	-0.21	-0.54	-1.20	-0.62	-0.2	-0.32	-0.33	-0.01	-0.16	-0.24	-0.32
1973	16..	-0.16	-0.19	-0.13	0.15	0.05	-0.15	-0.49	-0.59	-0.60	-0.66	-0.78	-0.65
1974	1690	-0.21	-0.29	-0.38	-0.37	-0.58	-0.47	0.00	0.12	0.28	-0.00	-0.14	-0.38
1975	1726	-0.12	-0.07	-0.03	0.20	0.21	-0.35	-0.00	-0.30	-0.45	-0.22	-0.37	-0.50
1976	1750	-0.44	-0.36	-0.19	-0.17	-0.07	-0.29	-0.30	-0.35	-0.22	-0.02	-0.14	-0.20
1977	1774	-0.03	0.32	0.22	0.40	0.74	0.78	0.67	0.56	1.00	1.00	1.00	1.00

DROUGHT SEVERITY INDEX VALUES — WATER DEMAND PRICE IS $2.00 PER THOUSAND GALLONS

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1966	[illegible]	-0.65	-0.65	-0.56	-0.60	[illegible]	-0.35	-0.10	-0.21	-0.07	-0.07	[illegible]	-0.26
1967	[illegible]	-0.22	-0.22	-0.12	-0.36	-0.43	-0.06	-0.65	-0.17	-0.31	-0.75	[illegible]	0.13
1968	[illegible]	0.05	0.06	0.15	0.13	-0.40	-0.30	-0.35	-0.02	-0.76	-1.06	-0.22	-0.21
1969	[illegible]	0.11	-0.05	0.15	-0.39	-0.81	-0.37	-0.70	-0.74	-1.03	-1.05	-0.24	-0.43
1970	1431	-0.46	-0.43	-0.47	-0.02	-0.36	-0.60	-0.80	-0.45	-0.36	-0.49	-0.65	-0.50
1971	[illegible]	-0.28	-0.53	-0.44	-0.90	-0.34	-0.50	-0.53	-0.30	-0.43	-0.16	-0.36	-0.42
1972	[illegible]	-0.41	-0.38	-1.00	-1.40	-0.76	-0.56	-0.44	-0.45	-0.16	-0.26	-0.55	-0.44
1973	[illegible]	-0.24	-0.30	-0.23	0.07	-0.63	-0.26	-0.06	-0.73	-0.74	-0.01	[illegible]	-0.77
1974	[illegible]	-0.52	-0.40	-0.56	-0.49	-0.72	-0.60	-0.09	0.04	0.22	-0.04	-0.25	-0.55
1975	[illegible]	-0.2	-0.15	-0.12	0.15	0.14	-0.47	-0.15	-0.41	-0.56	-0.33	-0.52	-0.53
1976	[illegible]	-0.57	-0.40	-0.30	-0.26	-0.17	-0.41	-0.42	-0.47	-0.35	-0.11	-0.24	-0.31
1977	1774	-0.13	0.26	0.15	0.34	0.71	0.76	0.64	0.52	1.00	1.00	1.00	1.00

Orangeville City

[illegible] SEVERITY INDEX VALUES — WATER DEMAND PRICE IS $0.20 PER THOUSAND GALLONS

YEAR	[illegible]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
[illegible]	[illegible]	[illegible]	[illegible]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-0.57	-0.97
[illegible]	[illegible]	[illegible]	-0.53	0.16	-0.07	-0.54	-0.16	-0.61	-0.56	-0.51	-0.59	-0.25	-0.16
[illegible]	[illegible]	[illegible]	[illegible]	-0.07	-0.02	-0.22	-0.03	-0.37	-0.12	-0.19	-0.22	-0.07	-0.16
[illegible]	[illegible]	[illegible]	0.16	0.16	-0.17	0.09	0.26	-0.26	-0.17	-0.05	-0.15	0.11	-0.60
[illegible]	[illegible]	[illegible]	0.00	0.07	0.09	-0.44	-0.12	-0.04	0.09	-0.20	-0.08	0.01	-0.16
[illegible]	[illegible]	-0.07	-0.35	[illegible]	0.05	-0.13	-0.29	-0.03	-0.28	-0.23	-0.08	0.19	0.29
[illegible]	[illegible]	[illegible]	[illegible]	-0.04	0.17	0.20	0.27	-0.01	-0.13	-0.21	-0.07	-0.20	0.06
[illegible]	[illegible]	[illegible]	[illegible]	0.12	0.21	0.16	-0.00	-0.22	-0.29	-0.11	-0.45	0.05	0.12
[illegible]	[illegible]	[illegible]	[illegible]	-0.12	0.02	1.34	-0.08	1.00	1.00	1.00	1.00	1.00	1.00

[illegible] SEVERITY INDEX VALUES — WATER [illegible] PRICE IS $0.50 PER THOUSAND GALLONS

YEAR	[illegible]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
[illegible]	[illegible]	[illegible]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-0.81	-1.27
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.24	-0.55	-0.36	-0.86	-0.79	-0.75	-0.60	-0.41	-0.25
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.37	-0.40	-0.25	-0.59	-0.29	-0.37	-0.41	-0.25	-0.36
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.55	-0.05	0.14	-0.45	-0.55	-0.22	-0.52	-0.02	-0.16
[illegible]	[illegible]	[illegible]	[illegible]	-0.07	-0.05	-0.60	-0.29	-0.20	-0.05	-0.36	-0.25	-0.14	-0.33
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.19	-0.31	-0.49	-0.19	-0.06	-0.42	-0.24	0.07	0.16
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.05	0.06	0.15	-0.16	-0.30	-0.39	-0.24	-0.39	-0.06
[illegible]	[illegible]	[illegible]	[illegible]	-0.31	0.09	0.05	-0.10	-0.41	-0.49	-0.26	-0.67	-0.10	-0.01
[illegible]	[illegible]	[illegible]	[illegible]	-0.29	-0.13	0.24	-0.25	1.00	1.00	1.00	1.00	1.00	1.00

[illegible] SEVERITY INDEX VALUES — WATER [illegible] PRICE IS $1.00 PER THOUSAND GALLONS

YEAR	[illegible]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
[illegible]	[illegible]	[illegible]	[illegible]	1.00	1.00	[illegible]	1.00	1.00	[illegible]	1.00	1.00	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	-0.73	[illegible]	-0.40	-0.75	-0.54	-1.10	[illegible]	-0.97	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-1.11	-0.59	-0.41	-0.79	[illegible]	-0.55	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.50	-0.16	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.19	-0.86	-0.46	-0.36	-0.19	-0.50	-0.41	-0.29	-0.51
[illegible]	[illegible]	[illegible]	-0.74	-0.27	-0.25	-0.48	-0.08	-0.35	[illegible]	-0.01	-0.40	-0.05	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	-0.35	-0.08	-0.04	0.04	-0.32	-0.47	-0.57	-0.40	-0.57	-0.19
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.03	-0.10	-0.31	-0.59	[illegible]	-0.45	-0.69	-0.24	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.28	0.13	-0.41	1.00	1.00	1.00	1.00	1.00	[illegible]

[illegible] SEVERITY INDEX VALUES — WATER DEMAND PRICE IS $2.00 PER THOUSAND GALLONS

YEAR	[illegible]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-1.36	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.61	[illegible]	-0.77	-1.42	-1.34	-1.27	-1.06	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.30	[illegible]	-0.89	-0.76	-0.58	-0.72	-0.33	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.57	-1.16	[illegible]	[illegible]	-0.37	[illegible]	-0.62	-0.49	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.70	-0.95	-0.55	[illegible]	-0.85	[illegible]	-0.21	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.51	[illegible]	-0.61	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-1.16	-0.45	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.00	[illegible]	1.00	1.00	1.00	1.00	1.00	[illegible]

Milford City data - August 1967-June 1977 (gallons)

							30540000.	14551300.	11650700.	8265300.	6212100.
6112900.	6099400.	9241600.	9608700.	20035500.	29176800.	28801400.	21807300.	20693500.	11204600.	7395700.	8593000.
6342000.	5998800.	9185100.	9698300.	27925300.	20527800.	28263800.	29628200.	21199900.	9118400.	6207700.	6571700.
6974300.	6996100.	8744300.	13696700.	28148300.	24228900.	29927800.	25906500.	19880700.	10809600.	7879500.	5957000.
7607500.	5776800.	8002900.	15043300.	20400400.	29909200.	33192200.	28307900.	10851400.	21922300.	7111100.	8033300.
7176500.	9410200.	16539900.	13971400.	27666400.	29672400.	35606600.	27369600.	17771000.	9319400.	13053400.	13052300.
5906200.	8399800.	9750500.	9750600.	13907400.	29588000.	34629600.	32662500.	10439900.	23415200.	8592500.	8591500.
7096600.	8087000.	8315500.	15857600.	37893800.	33626400.	34380100.	34274000.	16394400.	16394200.	7766000.	8210000.
8209600.	8210000.	8209000.	10667800.	17285500.	26779800.	31494400.	28494400.	26204900.	14696600.	8416700.	7619900.
7816700.	6975200.	9012300.	12327400.	32274100.	32274000.	30468700.	24282800.	24282900.	24282800.	11162000.	11963900.
16914500.	6914300.	9067300.	23953500.	16708000.	19643600.						

Monticello City data - January 1966-August 1977 (10,000 gallons)

1181.00	1046.00	1171.00	1632.00	2436.00	2634.00	2096.00	1914.00	1297.00	1017.00	933.00	832.00
856.00	786.00	830.00	1073.00	2344.00	1896.00	1953.00	1800.00	1550.00	1158.00	692.00	562.00
644.00	565.00	608.00	839.00	2238.00	2388.00	2431.00	1527.00	2050.00	1836.00	1237.00	760.00
640.00	612.00	601.00	1402.00	2809.00	2453.00	2967.00	2614.00	2275.00	1795.00	818.00	875.00
936.00	925.00	1001.00	932.00	2078.00	2784.00	3071.00	2067.00	1505.00	1272.00	1062.00	888.00
562.00	915.00	1029.00	1822.00	2114.00	2734.00	2746.00	1743.00	1629.00	1036.00	918.00	866.00
926.00	825.00	1500.00	2414.00	2925.00	2657.00	2703.00	2267.00	1320.00	1186.00	954.00	941.00
941.00	659.00	974.00	987.00	1812.00	2544.00	3208.00	2851.00	2196.00	1795.00	1446.00	1222.00
1000.00	944.00	1208.00	1613.00	3073.00	3290.00	2192.00	1615.00	1004.00	1102.00	946.00	1056.00
948.00	797.00	921.00	962.00	1563.00	3084.00	2372.00	2421.00	2070.00	1371.00	1161.00	1167.00
1237.00	1029.00	1079.00	1431.00	2160.00	3000.00	2958.00	2563.00	1767.00	1155.00	973.00	948.00
899.00	520.00	719.00	746.00	536.00	526.00	757.00	839.00				

Orangeville City data - November 1969-June 1977 (gallons)

										30524.00	71597.00
[illegible]	[illegible]	26117.00	30734.00	51131.00	50391.00	54441.00	49514.00	35660.00	25057.00	25515.00	41384.00
[illegible]	63670.00	55235.00	49491.00	49491.00	49490.00	49491.00	38066.00	29865.00	25562.00	23770.00	46762.00
46757.00	54656.00	26734.00	36047.00	39249.00	36034.00	46149.00	42397.00	28211.00	23528.00	20944.00	44220.00
55438.00	41135.00	34658.00	31504.00	60003.00	57060.00	42350.00	34874.00	33954.00	23484.00	24824.00	54049.00
55926.00	61773.00	37428.00	33676.00	53594.00	60565.00	43362.00	50609.00	36124.00	24151.00	20836.00	34510.00
[illegible]	40206.00	41211.00	30435.00	38939.00	40246.00	43666.00	45994.00	36431.00	24857.00	32059.00	45629.00
41546.00	55179.00	36030.00	29910.00	42452.00	56752.00	54591.00	54218.00	34723.00	34704.00	26236.00	45046.00
44956.00	38090.00	47423.00	38350.00	34414.00	63053.00						

Synthetic Severity Index Values (May-September)

-4.72	-2.50	-1.32	-0.38	-0.65
-3.98	-1.94	-1.24	0.12	0.30
-3.29	-1.57	-1.60	0.63	-1.11
-2.64	-2.13	-0.40	0.55	0.67
-3.46	-2.45	-1.47	-2.08	-3.72
-4.40	-2.57	-1.32	-0.12	-0.45
-3.61	-1.77	-1.25	0.12	-1.39
-4.47	-2.01	-1.28	-0.55	-0.82
-2.90	-2.19	-1.61	-0.66	-3.30
-3.53	-1.92	-1.07	0.63	0.31
-3.53	-2.64	-1.27	-0.61	-0.66
-3.92	-2.18	-1.07	0.62	-0.88
-2.70	-1.65	-1.20	-2.15	-3.34
-3.29	-1.89	-1.23	0.15	-1.10
-3.53	-2.21	-1.28	0.51	-0.09
-2.20	-1.93	-1.22	0.54	-1.21
-3.80	-2.35	-1.17	-0.53	-1.20
-2.87	-2.16	0.08	-0.06	0.18
-2.53	-2.38	-1.44	-1.78	-3.80
-3.46	-2.54	-1.44	-1.84	-4.25
-3.70	-1.82	-1.18	-0.61	-3.65
-4.24	-2.16	-1.07	-1.77	-3.73
[illegible]	-1.90	-0.96	-0.09	-0.94
-3.33	-2.30	-0.19	-1.90	-4.35
-3.09	-2.47	-1.22	-1.72	-3.13
-3.82	-1.90	-1.37	-0.46	-2.96
-4.67	-2.34	-1.12	-1.77	-0.84
-3.62	-2.56	-1.42	-1.86	-1.99
-2.79	-1.93	-0.44	-0.66	-0.97
-2.68	-1.97	-0.99	-1.62	-3.45
-4.00	-2.38	-1.61	-0.69	-1.23
-4.04	-2.31	-0.21	-0.33	-1.22
-2.77	-1.86	0.27	-1.67	-1.01
-2.96	-2.18	-1.49	-1.80	-2.96
-3.58	-2.47	-1.28	-1.52	-3.71
-4.35	-1.77	-0.99	-1.89	-4.03
-3.00	-2.14	-0.27	-0.83	-3.04
-3.09	-2.30	-1.16	-1.82	-3.44
-2.85	-2.51	0.09	-1.82	-4.10
-4.53	-2.37	-1.48	-1.92	-4.25
-4.41	-1.79	-0.30	-1.71	-3.41
-3.15	-1.82	-1.34	-1.72	-4.05
-3.64	-2.77	-1.63	-1.69	-3.33
-4.15	-1.77	-0.23	-2.02	-0.83
-4.13	-2.14	-1.05	-1.44	-4.66
-3.86	-2.37	-1.12	-1.53	-1.43
-3.27	-1.96	-1.64	-1.67	-1.47
-3.68	-1.87	0.72	-0.32	-0.66
-2.90	-2.18	-0.23	-1.82	-3.52
-3.54	-2.44	-1.39	-1.98	-1.14
-3.44	-2.36	-1.19	-1.99	-3.46
-4.44	-3.17	-1.06	-2.02	-3.29
-3.25	-2.55	-0.32	-1.85	-3.62
-3.35	-1.66	-1.17	-1.79	-3.86
-3.18	-2.31	0.23	-0.42	-0.91
-3.78	-2.95	-0.24	-1.81	-4.63
-3.18	-1.80	-1.29	-1.99	-3.43
-3.61	-1.92	-1.47	-1.48	-2.99
-4.56	-2.87	-0.37	-1.91	-3.88
-2.43	-1.85	-1.57	-1.82	-3.70
-3.48	-1.63	-1.40	-2.11	-3.09
-3.68	-1.93	-0.36	-1.96	-3.27
-2.66	-2.68	0.36	-1.81	-0.63
-2.66	-2.31	0.55	-1.63	-1.11
-3.16	-1.61	-1.20	-1.69	-3.95
-4.03	-1.73	-1.57	-2.03	-3.93
-3.14	-1.86	-0.51	-1.62	-0.87
-5.43	-2.69	-1.39	-1.33	-3.42
-3.69	-2.34	0.69	-0.15	-0.39
-3.95	-2.54	-1.15	-1.89	-3.66
-3.71	-2.27	-0.23	-1.69	-1.50
-3.48	-2.05	-1.40	-2.02	-0.44
-4.87	-2.26	-1.21	-1.94	-0.84
-4.21	-2.28	-1.40	-1.32	-5.85
-3.30	-1.96	-0.20	-1.98	-3.51
-3.50	-1.71	-0.21	-1.84	-0.92
-3.16	-2.70	-0.36	-1.79	-1.06
-4.29	-1.74	0.04	-1.79	-1.34
-5.47	-2.85	-0.17	-1.77	-3.58
-3.15	-2.33	-1.17	-1.71	-3.58
-3.09	-1.90	0.53	-0.80	-4.15
-3.31	-2.46	-0.32	-1.84	-3.77
-3.04	-2.69	-0.27	-2.01	-3.21

-5.91	-2.02	-1.44	-1.90	-3.64
-3.99	-2.21	0.44	-1.82	-4.04
-3.84	-3.49	0.02	-1.30	-4.65
-4.32	-2.09	-0.55	-1.54	-3.63
-3.71	-1.45	0.26	-1.51	-4.51
-4.56	-2.25	-1.34	-1.80	-3.81
-2.86	-2.15	-0.12	-1.74	-3.37
-4.35	-2.33	0.38	-1.67	-4.15
-4.39	-2.56	-0.16	-1.59	-3.13
-5.58	-2.34	0.31	-1.85	-4.13
-3.63	-2.79	-1.42	-1.86	-3.50
-3.51	-2.45	0.18	-1.43	-3.25
-3.78	-1.30	0.40	-0.72	-3.75
-2.72	-2.09	0.34	-1.64	-3.17
-5.70	-2.80	-1.50	-1.58	-3.45
-3.59	-2.38	-0.26	-1.58	-3.77
-2.74	-2.39	0.67	-0.49	-0.81
-4.09	-2.21	0.25	-1.55	-3.46
-3.26	-3.06	0.35	-1.51	-3.88
-4.47	-2.04	0.41	-1.74	-4.29
-4.54	-1.94	0.01	-1.97	-3.94
-3.63	-1.80	1.00	-1.60	-4.55
-3.49	-2.11	0.67	-1.97	-2.91
-4.25	-2.94	0.97	-1.65	-3.20
-3.12	-2.74	0.22	-1.78	-4.45
-3.24	-2.24	0.63	-1.85	-3.22
-3.08	-2.27	-0.09	-1.95	-3.43
-4.90	-1.88	0.19	-1.70	-3.77
-5.27	-1.81	-0.28	-1.61	-4.18
-4.55	-2.05	-0.24	-2.02	-3.29
-3.24	-2.38	0.54	-1.70	-4.42
-3.83	-2.38	-1.40	-2.20	-3.58
-5.93	-2.69	-0.52	-1.76	-3.78
-3.00	-1.60	-0.14	-1.61	-2.60
-3.93	-3.64	0.18	-1.36	-4.54
-4.97	-2.25	-0.21	-1.83	-3.09
-2.75	-1.93	-0.36	-1.70	-4.78
-3.49	-1.49	0.03	-1.91	-4.00
-3.50	-1.66	-1.23	-1.88	-3.43
-4.80	-1.96	0.39	-1.65	-3.69
-2.85	-1.90	-1.33	-1.63	-3.04
-4.41	-2.93	-1.20	-1.69	-3.85
-3.39	-2.69	-0.03	-1.90	-3.47
-4.80	-2.28	0.49	-1.85	-3.42
-4.46	-2.20	-0.26	-1.74	-3.67
-4.90	-2.23	-1.40	-1.52	-3.99
-5.00	-3.00	-1.43	-1.91	-3.67
-3.47	-2.12	-1.49	-1.83	-4.59
-3.97	-2.04	-1.41	-1.60	-3.78
-3.84	-2.08	-1.36	-1.64	-4.24
-2.79	-1.65	-1.09	-1.90	-3.77
-2.89	-2.03	-1.32	-1.96	-3.66
-3.20	-2.15	-1.50	-1.50	-3.59
-3.43	-3.05	-0.32	-1.67	-3.79
-4.23	-2.63	-0.27	-1.48	-4.38
-5.96	-2.44	-1.11	-1.70	-2.70
-3.42	-2.16	-1.24	-1.68	-3.98
-5.86	-2.42	-1.78	-1.65	-3.00
-3.55	-2.70	0.36	-1.61	-4.43
-4.08	-2.31	-1.43	-1.28	-3.03
-4.85	-1.67	-1.67	-1.67	-3.27
-3.39	-3.15	-1.29	-1.45	-2.94
-3.13	-2.78	-1.81	-1.78	-4.56
-5.07	-2.47	-1.55	-1.70	-5.83
-3.58	-2.59	-1.69	-1.80	-3.55
-3.55	-2.19	-0.10	-1.95	-4.65
-2.45	-2.09	-0.09	-1.82	-3.92
-3.73	-2.71	-0.25	-1.78	-3.54
-4.50	-1.98	0.43	-1.72	-4.18
-3.55	-1.96	-1.26	-1.99	-3.92
-3.80	-2.48	-1.32	-1.86	-4.36
-4.39	-2.66	-1.57	-1.64	-2.95
-2.66	-2.21	-0.33	-2.05	-3.31
-5.54	-1.85	-0.31	-2.17	-3.93
-3.59	-2.95	-1.69	-2.01	-3.81
-3.52	-2.11	-1.18	-1.94	-4.14
-3.72	-2.01	-1.07	-1.83	-3.68
-4.34	-2.71	-0.24	-1.93	-3.88
-4.11	-1.79	0.19	-0.73	-1.54
-3.81	-1.81	-0.45	-1.76	-3.50
-2.35	-1.83	-1.58	-1.97	-4.18
-3.40	-2.33	-1.52	-2.03	-4.36

Synthetic Seasonal Severity Index Values

-3,41	-2,12	-1,25	-1,84	-4,30
-3,92	-2,73	-1,49	-1,72	-4,67
-2,35	-2,26	-0,13	-1,50	-4,10
-3,51	-2,73	-1,25	-1,61	-4,90
-3,51	-2,49	-1,35	-1,74	-2,93
-3,65	-2,08	-1,55	-1,66	-2,66
-4,07	-2,43	-1,40	-1,80	-4,23
-4,03	-1,98	-1,39	-1,85	-4,01
-3,39	-2,80	-1,41	-1,55	-4,37
-2,85	-2,28	-1,56	-1,80	-3,61
-5,30	-1,83	-1,53	-1,84	-6,10
-2,93	-2,65	-1,38	-1,63	-3,28
-3,24	-2,06	-1,53	-1,81	-4,50
-3,84	-2,42	-1,55	-1,79	-3,51
-4,37	-1,61	-1,23	-2,00	-3,76
-3,16	-1,59	-1,31	-1,61	-4,18
-3,74	-2,73	-1,65	-1,74	-3,87
-3,58	-2,05	0,05	-0,51	-3,68
-3,09	-2,31	-1,32	-1,69	-4,09
-4,58	-1,70	-0,35	-2,01	-2,68
-3,71	-2,02	-1,48	-1,70	-3,91
-4,74	-2,95	-1,28	-1,53	-4,47
-3,72	-1,54	-1,29	-1,80	-4,25
-4,01	-2,63	-1,12	-2,22	-3,23
-3,28	-1,91	-1,93	-1,76	-4,05
-3,76	-3,19	-1,47	-1,67	-4,51
-4,04	-2,11	-1,43	-0,59	-3,61
-3,21	-2,47	-0,25	-1,79	-1,18
-4,09	-1,69	-1,30	-1,65	-3,84
-4,05	-1,57	-1,50	0,22	-0,32
-5,02	-2,22	-1,52	-1,80	-3,94
-3,96	-2,24	-1,30	-1,97	-4,24
-3,77	-1,81	-1,10	-1,53	-3,31
-2,59	-1,70	-1,18	-1,39	-3,59
-2,95	-2,27	-1,53	-1,72	-3,33

-1,64	-1,81	-2,40
-1,23	-1,98	-2,20
-1,27	-1,67	-2,06
-0,82	-2,03	-2,50
-2,43	-2,41	-1,55
-1,51	-1,79	-2,23
-1,39	-1,31	-1,92
-1,58	-1,61	-2,29
-1,99	-2,51	-2,46
-1,04	-1,98	-2,15
-1,61	-0,93	-2,35
-1,71	-1,80	-2,38
-2,03	-1,86	-2,55
-1,37	-1,81	-2,00
-1,23	-1,93	-1,64
-1,16	-1,61	-2,15
-1,63	-1,63	-1,23
-0,89	-1,75	-2,49
-2,21	-1,99	-2,40
-2,43	-1,58	-2,00
-1,84	-1,91	-1,87
-2,20	-1,87	-2,22
-1,27	-2,04	
-2,02	-2,63	
-2,14	-1,78	
-1,69	-2,45	
-1,67	-2,34	
-2,15	-1,58	
-1,27	-1,97	
-1,91	-2,02	
-1,86	-1,90	
-1,29	-1,73	
-1,31	-2,09	
-2,17	-1,86	
-2,22	-2,01	
-2,14	-2,40	
-1,65	-1,99	
-2,14	-1,91	
-1,87	-2,01	
-2,53	-2,35	
-1,91	-2,61	
-2,15	-2,38	
-2,42	-2,25	
-1,59	-2,28	
-2,15	-1,99	
-1,85	-2,19	
-1,95	-2,18	
-0,89	-2,10	
-1,67	-2,05	
-2,03	-2,23	
-2,25	-2,20	
-2,40	-2,51	
-2,03	-1,87	
-2,07	-2,13	
-1,13	-2,27	
-2,30	-2,19	
-2,14	-2,57	
-2,09	-2,67	
-2,28	-2,49	
-2,13	-2,01	
-2,20	-1,75	
-1,96	-2,04	
-1,34	-1,78	
-1,35	-2,26	
-2,03	-2,42	
-2,42	-2,33	
-1,56	-1,91	
-2,33	-2,14	
-0,81	-2,61	
-2,31	-2,26	
-1,66	-2,14	
-1,83	-2,13	
-1,98	-1,28	
-2,36	-1,96	
-1,92	-2,19	
-1,48	-2,47	
-1,72	-2,26	
-1,57	-2,53	
-2,15	-1,75	
-2,15	-2,36	
-1,38	-2,22	
-2,04	-2,16	
-2,04	-2,44	
-2,46	-2,33	
-1,79	-2,37	
-2,05	-2,27	
-2,07	-2,57	
-1,65	-2,20	
-2,38	-2,34	

Table B.1. MILFORD IRRIGATION DATA

Year	Acres Irrigated	Irrigation Pumpage	Severity Index S
1958	9866	36595	0.17
1959	12621	40564	0.26
1960	12666	46064	0.22
1961	13043	40909	0.29
1962	13155	42718	0.22
1963	13407	42032	0.29
1964	13447	44117	0.20
1965	13495	43504	0.16
1966	13655	49270	0.20
1967	13655	45657	0.22
1968	13655	46024	0.18
1969	13622	49782	0.22
1970	13743	55274	0.08
1971	13804	56105	0.05
1972	13804	53870	0.11
1973	13806	47664	0.15
1974	13738	59170	0.02
1975	13767	52604	0.00
1976	13804	53558	0.07
1977	13848	48229	0.20

Table B.2. OBERTO DITCH IRRIGATION DATA.

Year	Acres Irrigated	Diversion From Price River	Severity Index S
1942	66	897	-1.11
1943	66	876	-0.98
1944	66	807	-0.86
1945	66	1165	-1.70
1946	66	565	-0.41
1947	66	650	-0.43
1948	66	604	-0.32
1949	96	572	0.13
1950	96	918	-0.49
1951	96	635	0.03
1952	96	236	0.65
1953	96	361	0.44
1954	96	348	0.50
1955	84	163	0.66
1956	84	356	0.41
1957	84	269	0.52
1958	84	225	0.59
1959	84	271	0.51
1960	66	261	0.41
1961	66	230	0.46
1962	66	414	0.01
1963	66	189	0.56
1964	66	331	0.17
1965	66	341	0.06
1966	66	353	0.15
1967	66	402	-0.02
1968	66	439	-0.06
1969	66	394	0.15
1970	66	405	0.09
1971	66	483	-0.10
1972	66	398	0.14
1973	66	547	-0.29
1974	66	518	-0.08
1975	66	509	-0.29
1976	66	296	0.32

Table B.3. LOGAN IRRIGATION AREA DATA.

Year	Acres Irrigated	Diversion From Logan River	Severity Index S
1931	2400	11170	0.12
1932	2400	23900	-1.08
1933	2400	18470	-0.53
1934	2400	8010	0.36
1935	2400	16850	-0.41
1936	2400	23090	-0.82
1937	2400	18990	-0.56
1938	2400	18950	-0.63
1939	2400	15890	-0.35
1940	2400	14790	-0.13
1941	2400	12449	-0.11
1942	2400	13317	-0.17
1943	2400	20670	-0.82
1944	2400	11450	-0.65
1945	2400	17450	-0.80
1946	2400	22570	-0.95
1947	2400	17710	-0.54
1948	2400	19370	-0.72
1949	2400	19130	-0.68
1950	2400	20360	-0.97
1951	2400	19830	-0.84
1952	2400	21170	-0.80
1953	2400	17180	-0.52
1954	2400	15730	-0.39
1955	2400	15030	-0.33
1956	2400	17520	-0.50
1957	2400	16080	-0.41
1958	2400	18270	-0.49
1959	2400	16990	-0.52
1960	2400	15670	-0.31
1961	2400	11888	0.03
1962	2400	14300	-0.27
1963	2400	13610	-0.15
1964	2400	13230	-0.21
1965	2400	16880	-0.68
1966	2400	15250	-0.29
1967	2400	14573	-0.29
1968	2400	15350	-0.46
1969	2400	16160	-0.36
1970	2400	13938	-0.23
1971	2400	13089	-0.17
1972	2400	19940	-0.74
1973	2400	16160	-0.46
1974	2400	21530	-0.80
1975	2400	18236	-0.72
1976	2400	16820	-0.50
1977	2400	7700	0.33

Appendix C

Computer Programs

Program for Municipalities (S)

```
C
C       THIS PROGRAM CALCULATES THE DROUGHT SEVERITY INDEX VALUES
C       FOR THE MUNICIPALITIES.
C
C
C
C       CALCULATION OF THE MONTHLY MUNICIPAL DEMAND (DM) IN MILLIONS
C       OF GALLONS AND THE DROUGHT SEVERITY INDEX (S) IN EQUATIONS
C            DM = DMD * DAYS * MW * POP / 1000000.
C       AND   S = 1 - F/DM
C       WHERE
C       DMD = MONTHLY  DEMAND CALCULATED BY THE EQUATION
C           =    40.75 + 30.54 * NATURAL LOG OF (1/C) + 24.14 * I
C                AND C = COST OF WATER IN DOLLARS
C                AND I = OUTDOOR USE INDEX
C       DAYS = 365 DAYS PER YEAR
C       MW = MONTHLY WEIGHT
C       POP = POPULATION
C
C
C
C
C
C
C
C
C
      DIMENSION F(80,12), MW(12), YEAR(80), POP(80), S(80,12), DM(80,12)
      REAL MW
C
C        INITIALIZE THE NUMBER OF YEARS OF RECORD
      N=12
C
C
C        READ IN MONTHLY WEIGHTS IN 12F5.3 FORMAT
      READ(5,111)(MW(J),J=1,12)

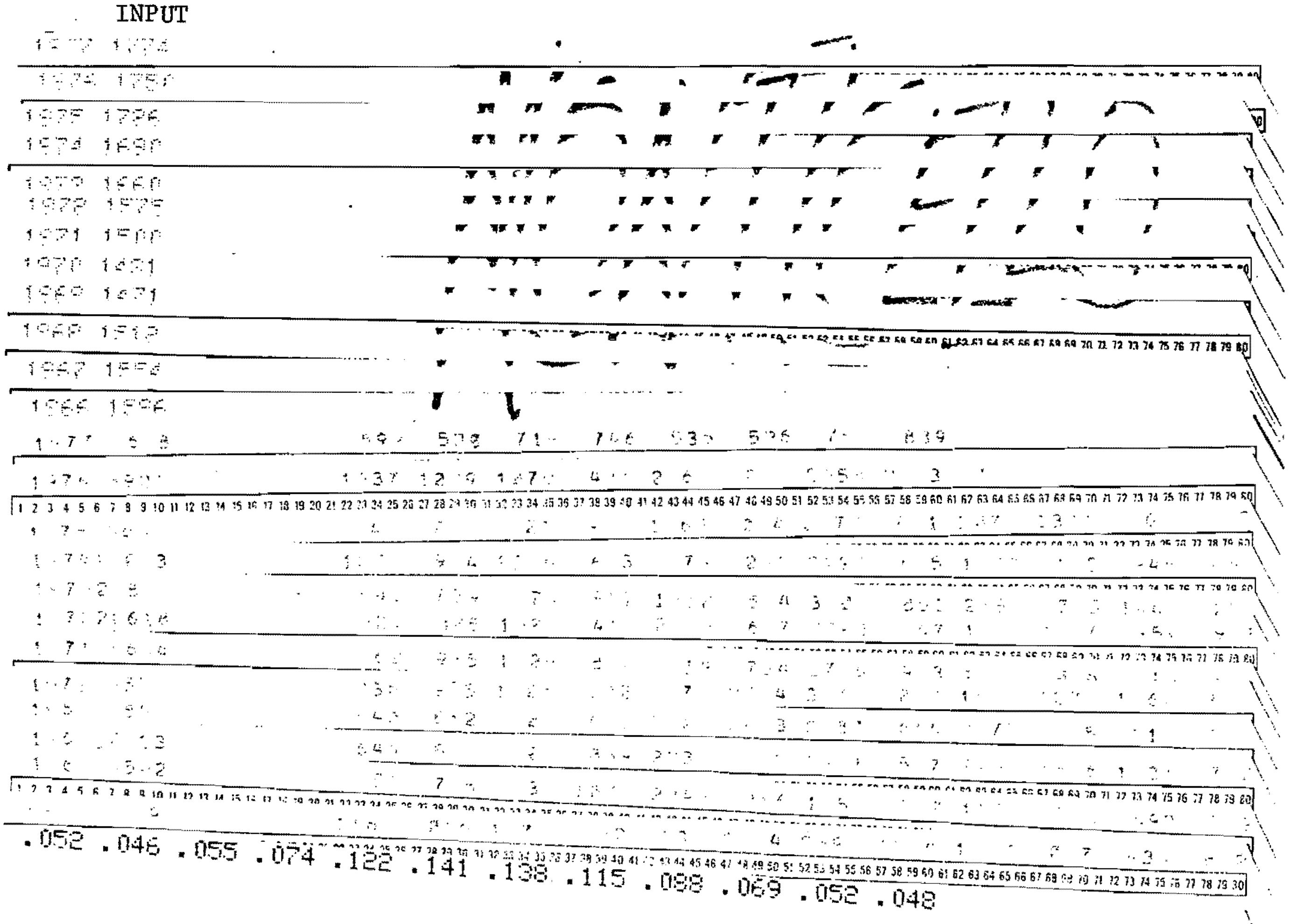
  111 FORMAT(12F5.3)
      WRITE(6,600)(MW(J),J=1,12)

  600 FORMAT(1X,'MW',12F10.3)
C        READ IN THE MONTHLY FURNISHED DEMAND (F)
      DO 1 I=1,N
      READ(5,110)(F(I,J),J=1,12)
  110 FORMAT(20X,12I5)
      WRITE(6,601)(F(I,J),J=1,12)
  601 FORMAT(1X,'F',12F10.2)
    1 CONTINUE
C
C        PUT F IN CORRECT UNITS (MILLIONS OF GALLONS)
      DO 10 I=1,N
      DO 10 J=1,12
   10 F(I,J) = F(I,J) / 100.0
C
C        READ IN YEAR AND POPULATION VALUES
      DO 3 I=1,N
      READ(5,120) YEAR(I), POP(I)

  120 FORMAT(2I5)
    3 CONTINUE
C
C        CALCULATION OF THE DROUGHT SEVERITY INDEX
C
C        INITIALIZE THE COST FUNCTION
      C = 0.2
    9 CONTINUE
      DO 77 II=1,4
      DMD = 40.75 + 30.54 * ALOG(1./C) + 24.14 * 9.
      DO 7 I=1,N
      DO 7 J=1,12
      DM(I,J) = DMD * 365. * MW(J) * POP(I) / 1000000.
    7 S(I,J) = 1. - F(I,J) / DM(I,J)
      IF(II.EQ.1) GO TO 61
      IF(II.EQ.2) GO TO 62
      IF(II.EQ.3) GO TO 63
   64 WRITE(6,774)
  774 FORMAT(1H1,/// T20,'DROUGHT SEVERITY INDEX VALUES', 10X,
     *'WATER DEMAND PRICE IS $2.00 PER THOUSAND GALLONS',/)
      GO TO 250
C        FORMAT STATEMENTS AND CONTROLS FOR PRINTING RESULTS
  229 DO 41 I=1,N
      WRITE(6,230) YEAR(I), POP(I),(S(I,J),J=1,12)
  230 FORMAT(2X,2I5,12F10.2)
   41 CONTINUE
      IF(II.EQ.4) GO TO 99
   77 CONTINUE
```

```
C
C        PAGE HEADINGS
  61 WRITE (6,771)
 771 FORMAT(1H1,/// T20,'DROUGHT SEVERITY INDEX VALUES', 10X,
    *'WATER DEMAND PRICE IS $0.20 PER THOUSAND GALLONS',/)
     C=0.50
     GO TO 250
  62 WRITE(6,772)
 772 FORMAT(1H1,/// T20,'DROUGHT SEVERITY INDEX VALUES', 10X,
    *'WATER DEMAND PRICE IS $0.50 PER THOUSAND GALLONS',/)
     C=1.00
     GO TO 250
  63 WRITE(6,773)
 773 FORMAT(1H1,/// T20,'DROUGHT SEVERITY INDEX VALUES', 10X,
    *'WATER DEMAND PRICE IS $1.00 PER THOUSAND GALLONS',/)
     C=2.00
C
 250 WRITE(6,770)
 770 FORMAT(1X,
    *'  YEAR  POP',7X,'JAN',7X,'FEB',7X,'MAR',7X,'APR',7X,'MAY',7X,
    *'JUN',7X,'JUL',7X,'AUG',7X,'SEP',7X,'OCT',7X,'NOV',7X,'DEC')
     GO TO 229
  99 CONTINUE
     STOP
     END
```

INPUT



OUTPUT: See Appendix B

Program for Irrigation Area (S)

```
C
C
C        THIS PROGRAM CALCULATES THE DROUGHT SEVERITY INDEX FOR
C        IRRIGATION AREAS GIVEN THE MONTHLY CROP GROWTH STAGE
C        COEFFICIENT (KC) FOR ALFALFA, MONTHLY PERCENT OF DAYTIME
C        HOURS (P), AVERAGE MONTHLY TEMPERATURES (T), NUMBER OF
C        ACRES IRRIGATED AND THE AMOUNT OF WATER PUMPED OR DIVERTED.
C
      DIMENSION KC(6),P(6),T(80,6),YEAR(80),ACRE(80),IP(80)
      DIMENSION U(80),SMALLU(80,6),KT(80,6),SUM(80),DI(80),S(80)
      REAL KC,IP,KT
C
C        INITIALIZE THE NUMBER OF YEARS
      N=35
C
C        INITIALIZE THE FARM IRRIGATION EFFICIENCY E
      E = 0.PO
C
C        READ IN THE MONTHLY CROP COEFFICIENT (MONTH 1 = APR; MONTH 6 =  SEP)
      READ(5,110)(KC(J),J=1,6)
  110 FORMAT(6F5.2)
C
C        READ IN PERCENT OF DAYTIME HOURS
      READ(5,110)(P(J),J=1,6)
C
C        READ IN  AVERAGE MONTHLY TEMPERATURES FOR THE LOCATION
C        (MONTH 1 = APRIL; MONTH 6 = SEPTEMBER)
      DO 1 I=1,N
      READ(5,110)(T(I,J),J=1,6)
    1 CONTINUE
C
C
C        READ IN NUMBER OF ACRES (ACRE(I)) FOR EACH YEAR
      READ(5,112)(ACRE(I),I=1,N)
  112 FORMAT(35I2)
C
C        READ IN YEAR AND AMOUNT OF WATER DIVERTED
      DO 2 I=1,N
      READ(5,100) YEAR(I), IP(I)
  100 FORMAT(2I5)
    2 CONTINUE
C
C        CALCULATION OF THE MONTHLY AND SEASONAL CONSUMPTIVE USE
      DO 7 I=1,N
      DO 7 J=1,6
      KT(I,J) = 0.0173 * T(I,J) - 0.314
      SMALLU(I,J) = KC(J) * KT(I,J) * T(I,J) * P(J) / 100.0
C
C        PUT CONSUMPTIVE USE VALUES IN FEET
      SMALLU(I,J) = SMALLU(I,J)  / 12.
    7 CONTINUE
      DO 8 I=1,N
      U(I) = SMALLU(I,1) + SMALLU(I,2) + SMALLU(I,3) +
     * SMALLU(I,4) + SMALLU(I,5) + SMALLU(I,6)
      WRITE(6,600)(SMALLU(I,J),J=1,6),U(I)
  600 FORMAT (1X,7F15.5)
    8 CONTINUE
      DO 9 I=1,N
C
C        CALCULATE THE IRRIGATION DEMAND FOR EACH SEASON
      DI(I) = U(I) * ACRE(I) / E
C
C        CALCUALTE THE SEASONAL DROUGHT SEVERITY INDEX (S)
      S(I) = 1.00 - IP(I) / DI(I)
      WRITE(6,610) YEAR(I), ACRE(I), IP(I), S(I)
  610 FORMAT(1X,3I10,F10.2)
    9 CONTINUE
      DO 766 I=1,N
      WRITE(7,767) S(I), YEAR(I)
  767 FORMAT(2F10.2)
  766 CONTINUE
      STOP
      END
```

INPUT Data

```
1975  500  406  107                         20   61   70  117  [illegible]   90   58   12
1973  547  402  105                              77  138  119   93  100   20
6666666666666669696969696969696964646464646666666666666666666666666666666666666
00000000000000000000000
3.92 9.9910.0710.20 9.32 8.39     OBERTO   HELPER AREA
```

OUTPUT - See Table B-2

Program to generate synthetic streamflow data
(writes output to disk storage)

```
FILE  8(KIND=DISK,MAXRECSIZE=14,BLOCKSIZE=420,AREAS=100,AREASIZE=120,
     * SAVEFACTOR=999,TITLE="LOGANRSYNTHETIC")

      DIMENSION Z(3000),A(3000),LR(250,12),TI(250,16),TEMPM(6),STDEV(6)
      DIMENSION C(3000)
      REAL LR
      SIGMA=SQRT(287)*338.58
      INTEGER T
C
C     INITIALIZATION OF THE BOX-JENKINS MODEL FOR THE LOGAN RIVER
C
      DO 10 I=1,25
      Z(I)=0.00
      A(I) =0.00
   10 CONTINUE
      Z(10)=19148.72
      Z(11)=13492.55
      Z(12)=11328.51
      Z(13)=9822.34
      Z(14)=7992.13
      Z(15)=7272.98
      Z(16)=6759.36
      Z(17)=5990.21
      Z(18)=7118.30
      Z(19)=14736.60
      Z(20)=34912.55
      Z(21)=35715.32
      Z(22)=19148.72
      Z(23)=13492.55
      Z(24)=11328.51
      P1=0.63157
      T12=0.80365
C
C     CALCULATE THE ERROR TERM A(T)
C
      DO 1 I=1,3000
      A(I) = SIGMA*RNOR(IR)
    1 CONTINUE
C
C     GENERATE SYNTHETIC STREAMFLOW FOR THE LOGAN RIVER
C     DATA IS TOTAL MONTHLY ACRE-FEET   OCTOBER-SEPTEMBER
C
      DO 2 T=25,3000
      Z(T) = P1*(Z(T -1) - Z(T-13)) + Z(T-12) + A(T) - T12*A(T-12)
      IF(Z(T).LE.(0.1)) GO TO 6
    7 CONTINUE
      GO TO 2
C
C        CHANGE NEGATIVE FLOW VALUE TO A VALUE THAT EXPRESSES
C        THE RECESSION OF THE STREAM.
C
    6 DMY = ALOG(ALOG(Z(T-1))) - 0.025
      Z(T) = EXP(EXP(DMY))
      GO TO 7
    2 CONTINUE
      DO 37 I=1,3000
       XI=I
       AZ = Z(I) + 10.
       WRITE(8,801) XI,Z(I), C(I), AZ
  801  FORMAT(4F10.2)
       WRITE(6,601) XI, Z(I), C(I), AZ

  601  FORMAT(1X, 4F10.2)
   37  CONTINUE
       LOCK 8
       STOP
       END
C     NORMAL INDEPENDENT RANDOM NUMBER GENERATOR

      FUNCTION RNOR(IR)
      DATA I/0/
      IF(I.GT.0)GO TO 30
   10 X=2.0 * RANDOM(IR) - 1.0
      Y=2.0 * RANDOM(IR) - 1.0
      S=X*X+Y*Y
      IF(S.GE.(1.0))GO TO 10
      S=SQRT(-2.0*ALOG(S)/S)
      RNOR=X*S
      GO2=Y*S
      I=1
      GO TO 40
   30 RNOR=GO2
      I=0
   40 RETURN
      END
```

Numerical integration program

```
      DIMENSION XPRIME(20),WX(20)
      REAL MEAN
      XPRIME(1) = 0.183435
      XPRIME(2) =-0.183435
      XPRIME(3) =0.525532
      XPRIME(4) =-.525532
      XPRIME(5) = 0.796666
      XPRIME(6) =-0.796666
      XPRIME(7) = 0.960290
      XPRIME(8) =-0.960290
      WX(1) = 0.362684
      WX(2) = 0.362684
      WX(3) = 0.313707
      WX(4) = 0.313707
      WX(5) = 0.222381
      WX(6) = 0.222381
      WX(7) = 0.101229
      WX(8) = 0.101229
      ADJ1 = 0.5000
      ADJ2 = 10.5000
C        READ IN MEAN AND STANDARD DEVIATION
      DO 1 J=1,18
      READ(5,100) MEAN, SD

  100 FORMAT(F7.5,F10.7)
      AREA = 0.00
      DO 2 I=1,8
      X=XPRIME(I) * ADJ1 + ADJ2
      XX=(EXP(((ALOG(X)-MEAN)**2)/(-2*(SD**2))))/(X*SD*2.506628275)
      AREA = AREA + WX(I) * XX
    2 CONTINUE
      AREA = AREA * ADJ1
      WRITE(6,600) J, AREA

  600 FORMAT(T20,I2,F15.8)
    1 CONTINUE
      STOP
      END
```

INPUT

OUTPUT

1	0.15509338
2	0.10418548
3	0.07517389
4	0.05353315

Program to Rank Data for U-Test

```
BEGIN

COMMENT;

  DEBUG; SORTING, RANKING, AND RANK SUMS FOR LOGAN RIVER FLOW DATA
                                                                  ;
FILE CR (KIND=READER,MAXRECSIZE=14),

     LP (KIND=PRINTER,MAXPECSIZE=22);

 INTEGER FND1,BEGIN2,END2
                                         ;
 END1 :=300;        % THIS CARD DEFINES WHERE THE FIRST DATA SET ENDS
 BEGIN2 :=301;      % THIS CARD DEFINES WHERE THE SECOND DATA SET STARTS
 END2 :=900;    %  THIS CARD DEFINES END2 WHICH IS THE LAST DATA POINT
 BEGIN
INTEGER ARRAY DATAP[1:END2], DATAPS[1:2,1:END2], OBUF[1:24];

INTEGER I, J, TEMP1, TEMP2, OBUFI, YEAR, MONTH;

PROCEDUPE SUMGROUPRANK (GROUP,Y1,Y2);
%
%  THIS PROCEDUPE WILL PRINT THE RANK TABLE FOR ONE OF THE 38 YEAR
%  PERTODS, INCORPORATING DATA FOR MONTHS Y1 THROUGH Y2
%
  INTEGER GROUP, Y1, Y2;
  BEGIN
  INTEGER SUMRANK;

  WRITE (LP[SKIP 1]);     %  WRITE HEADINGS
  WRITE (LP,<"GROUP ",I1//
            6("MO/YR  RANK    ")/6("-----  ----    ")/>,GROUP);
  OBUFI:=1;                %   THIS VARIABLE INDEXES THE BUFFER ORUF
  SUMRANK:=0;

  FOR I := Y1 STEP 1 UNTIL Y2 DO
    BEGIN;
    YEAR := (I-2) DIV 12 + 1;        %   COMPUTE YEAR GIVEN ABSOLUTE MNTH
    MONTH := (I+9) MOD 12;           %   COMPUTE MONTH WITHIN YEAR
                                     %   (ADD 9 FOR WATER YEAR FORMAT)
    IF MONTH = 0 THEN MONTH := 12; %   CORRECT FOR 12 MOD 12 = 0
    OBUF[OBUFI]:=MONTH;        %   NOTE: OBUF IS USED TWICE WITHIN THE
    OBUF[OBUFI+1]:=YEAR;       %   PROGRAM AS AN OUTPUT BUFFER FOR
    OBUF[OBUFI+2]:=DATAP[I]; %   VARIOUS TABLE INFORMATION
    SUMRANK:=*+DATAP[I];       %   ADD ONE RANK TO SUM OF RANKS
    IF OBUFI = 16 THEN         %   IT'S TIME TO PRINT A LINE
      BEGIN;
      WRITE (LP,<9(I2,"/",I2,X3,I3,X3)>,
                     FOR J := 1 STEP 1 UNTIL 18 DO OBUF[J]);
      OBUFI:=1;     %   RESET OBUFI TO 1
      END
    ELSE

       OBUFI:=*+3;  %    INCREMENT FOR NEXT FIELD
     END;
   WRITE (LP,<18(I2,"/",I2,X3,I3,X3)>,  %   OUTPUT LAST LINE
                   FOR J := 1 STEP 1 UNTIL OBUFI-1 DO OBUF[J]);
   WRITE (LP,<//"RANK TOTAL FOR THIS GROUP =",I15>,SUMRANK);

   END;

READ (CR,<16I5/(16I5)>,DATAP);  %   INPUT DATA
 % WRITE (LP,<"ECHO OF INPUT DATA:"//12(X1,I8)>,DATAP);
FOR I := 1 STEP 1 UNTIL END2 DO  %   MOVE DATA TO DATAPS FOR SORT
  BEGIN;
  DATAPS[1,I]:=I;
  DATAPS[2,I]:=DATAP[I];
  END;
FOR I := 1 STEP 1 UNTIL (END2-1) DO    % THIS IS THE BUBBLE SORT- CRUDE,
  FOR J := 1 STEP 1 UNTIL (END2-I) DO    %   BUT EFFECTIVE
   IF DATAPS[2,J] < DATAPS[2,J+1] THEN  %   TEST FOR SWITCH
    BEGIN;
    TEMP1:=DATAPS[1,J];
    TEMP2:=DATAPS[2,J];
    DATAPS[1,J]:=DATAPS[1,J+1];
    DATAPS[2,J]:=DATAPS[2,J+1];
    DATAPS[1,J+1]:=TEMP1;
    DATAPS[2,J+1]:=TEMP2;
    END;
```

```
FOR I := 1 STEP 1 UNTIL END2 DO     %   NOW MOVE RANKS TO DATAP
                                    %   (IN YEAR ORDER)
  DATAP(DATAPS(1,I)):=I;
OBUFI:=1;
WRITE (LP(SKIP 1));      %   HEADINGS FOR FIRST TABLE
WRITE (LP,<6("RANK  MO/YR  READ    ")/6("----  -----  -----   ")/>);

FOR I := 1 STEP 1 UNTIL END2 DO
  BEGIN;
  OBUF(OBUFI):=I;
  YEAR:=(DATAPS(1,I)-1) DIV 12 + 1;
  MONTH:=(DATAPS(1,I)+9) MOD 12;
  IF MONTH = 0 THEN MONTH :=12;
  OBUF(OBUFI+1):=MONTH;
  OBUF(OBUFI+2):=YEAR;
  OBUF(OBUFI+3):=DATAPS(2,I);
  IF OBUFI = 21 THEN      %   BUFFER FULL- TIME TO WRITE
    BEGIN;
    WRITE (LP,<6(X1,I3,X2,I2,"/",I2,X2,I5,X3)>,OBUF);
    OBUFI:=1;        %   RESET TO ONE
    END
  ELSE
    OBUFI:=*+4;      %   INCREMENT FOR NEXT FIELD
  END;
SUMGROUPRANK (1,1,END1);       %   FIND FIRST GROUP RANK SUM
SUMGROUPRANK (2,BEGIN2,END2);%   AND NOW THE SECOND GROUP
 END;

END.
```

INPUT

```
 9600 7980 7000 6520 5420 5780 778010140 9670 6770 5740 487099999
5929044750196501364011450 9480 8730 7730 7030 796015260437103570020410135801120
 5740 871016970506905807027030166001285010350 8490 7490 6930 5860 6820 778029490
1256010630 9340 8220 6720 7220 940033670303901698011940 9500 8240 7610 7050 6710
806504375022350161901393011380 9870 9390 7990163502450055320632703039018850143000
 5710 6230 837033530486002245013360 9980 8800 8600 8170 9150 8520102402528053490
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80
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OUTPUT

10/72	757	11/73	519	12/73	602	1/73	634	2/73	876	3/73	413
4/73	140	5/73	224	6/73	223	7/73	893	8/73	628	9/73	610
10/73	820	11/74	401	12/74	299	1/74	336	2/74	347	3/74	57
4/74	10	5/74	28	6/74	204	7/74	529	8/74	218	9/74	471
10/74	751	11/75	636	12/75	619	1/75	629	2/75	637	3/75	164
4/75	107	5/75	32	6/75	56	7/75	395	8/75	278	9/75	576

RANK TOTAL FOR THIS GROUP =   207946

VITA

D. T. Jensen

Candidate for the Degree of

Doctor of Philosophy in Engineering

Dissertation: Vulnerability of Water Supply Systems to Drought

Major Field: Water Resources and Hydrology

Biographical Information:

Personal Data: Born at Spanish Fork, Utah, June 5, 1940, son of Dean George and Blanche Jones Jensen; married Marilyn Brinton June 2, 1967; Five children - Joseph Brinton, Marjorie, Christy Ann, Amy and Kathleen.

Education: Attended elementary schools in Spanish Fork, Utah; graduated from Spanish Fork High in 1958; received the Bachelor of Arts degree from Brigham Young University, with a major in Political Science in 1967; did graduate work at Brigham Young University in Education in 1967-68; received Bachelor of Science degree from the University of Utah with a major in Meteorology, in 1972; did graduate work at Portland State University, 1973-75; received Master of Science degree from Utah State University with a major in Water Resources and Hydrology in 1976; completed requirements for the Doctor of Philosophy degree specializing in Water Resources and Hydrology, at Utah State University, in 1977.

Professional Experience: 1958 to 1962 served as an aerographer in the U.S. Marine Corps; forest service guard, 1965; taught and coordinated efforts of 14 teachers in Northern Arizona 1968-69; Laboratory assistant in meteorology at University of Utah, 1969-72; hydrometeorologist, hydrologist and river forecaster, National Weather Service in Salt Lake City, Utah and Portland, Oregon, 1971, 1972-75; research assistant, Utah Water Research Laboratory, Utah State University, 1976-1977.